AD-A188 470 ULTRA-HIGH SPEED INTEGRATED OPTICAL WAVEGUIDE DEVICES FOR OPTICAL COMPUTING(U) TACAN CORP CARLSBAD CA M M SALOUR SEP 87 RADC-TR-87-141 F19628-86-C-0185 1/1

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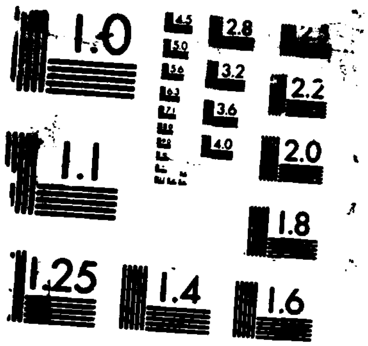


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AD-A188 470

RADC-TR-87-141
Final Technical Report
September 1987

# ULTRA-HIGH SPEED INTEGRATED OPTICAL WAVEGUIDE DEVICES FOR OPTICAL COMPUTING

TACAN Corporation

Michael M. Salour



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87 12 16 256

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SECURITY CLASSIFICATION OF THIS PAGE

# REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

| | |
|---|---|
| 1a. REPORT SECURITY CLASSIFICATION<br>UNCLASSIFIED | 1b. RESTRICTIVE MARKINGS<br>N/A |
| 2a. SECURITY CLASSIFICATION AUTHORITY<br>N/A | 3. DISTRIBUTION/AVAILABILITY OF REPORT<br>Approved for public release; distribution unlimited. |
| 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE<br>N/A | |
| 4. PERFORMING ORGANIZATION REPORT NUMBER(S)<br>N/A | 5. MONITORING ORGANIZATION REPORT NUMBER(S)<br>RADC-TR-87-141 |
| 6a. NAME OF PERFORMING ORGANIZATION<br>TACAN Corporation<br>6b. OFFICE SYMBOL (If applicable) | 7a. NAME OF MONITORING ORGANIZATION<br>Rome Air Development Center (DCLW) |
| 6c. ADDRESS (City, State, and ZIP Code)<br>2111 Palomar Airport Road, Suite 270<br>Carlsbad CA 92009 | 7b. ADDRESS (City, State, and ZIP Code)<br>Griffiss AFB NY 13441-5700 |
| 8a. NAME OF FUNDING/SPONSORING ORGANIZATION<br>Electronic Systems Division<br>8b. OFFICE SYMBOL (If applicable)<br>XR | 9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER<br>F19628-86-C-0185 |
| 8c. ADDRESS (City, State, and ZIP Code)<br>Hanscom AFB MA 01731-5000 | 10. SOURCE OF FUNDING NUMBERS<br>PROGRAM ELEMENT NO. 62702F<br>PROJECT NO. 06RA<br>TASK NO SB<br>WORK UNIT ACCESSION NO. IR |

11. TITLE (Include Security Classification)
ULTRA-HIGH SPEED INTEGRATED OPTICAL WAVEGUIDE DEVICES FOR OPTICAL COMPUTING

12. PERSONAL AUTHOR(S)
Michael M. Salour

| 13a. TYPE OF REPORT | 13b. TIME COVERED | 14. DATE OF REPORT (Year, Month, Day) | 15. PAGE COUNT |
|---|---|---|---|
| Final | FROM Jul 86 TO Jan 87 | September 1987 | 80 |

16. SUPPLEMENTARY NOTATION
N/A

17. COSATI CODES

| FIELD | GROUP | SUB-GROUP |
|---|---|---|
| 20 | 06 | 01 |

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Ultra-High Speed Waveguide Devices for Optical Computing,

19 ABSTRACT (Continue on reverse if necessary and identify by block number)


We have studied ultra-high speed waveguide devices for optical computing and logic operation that are compatible with the pulse-power and repetition rates available with picosecond pulses from a mode-locked semiconductor diode laser. Numerous variations of such logic operations have been implemented in our laboratories for the direct measurement of on-chip propagation delays and waveforms in Gigahertz logic circuits with unprecedented (~10 ps) resolution and accuracy. We have also studied and performed experiments with optical circuits made with semiconductors and nonlinear polymers. Such circuits should eventually have considerable performance, reliability and cost benefits over similar components made with many alternative materials, because of the ability to integrate waveguide devices with optical sources, detectors and electronic circuitry. We have shown that although at present the performance of semiconductor waveguide devices is inferior to that of devices made with lithium niobate, progress is rapid and there seem no fundamental reasons why semiconductor devices should not eventually give performance


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|---|---|
| 20 DISTRIBUTION/AVAILABILITY OF ABSTRACT<br>☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS | 21 ABSTRACT SECURITY CLASSIFICATION<br>UNCLASSIFIED |
| 22a NAME OF RESPONSIBLE INDIVIDUAL<br>Donald J. Nicholson | 22b TELEPHONE (Include Area Code) (315) 330-4092<br>22c OFFICE SYMBOL RADC (DCLW) |

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

comparable with many non-semiconductor devices. A wide range of waveguide optical devices using nonlinear polymers will be examined under Phase II for integration in optical integrated circuits. As continued improvements in electronic speed and power begin to slow, optics and optical circuits with novel nonlinear material will assume a role of increasing importance in our quest to maintain computational superiority in the U.S. over our rivals in both the economic and national security realms.

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## 1. Introduction

A number of recent developments have increased the interest in digital optical signal-processing devices and techniques. Laser technology has now advanced to the point that optical fiber communication systems are being widely installed and integrated-optics spectrum analyzers have been developed.

In the research stage, it has been shown that optical fibers can be used to transmit information at rates approaching 1 THz. This rate is much beyond the capabilities of any presently known electronic light detector. Thus, to utilize this information-handling capacity, some form of optical signal processing will have to be performed before the light signals are converted to electronic ones.

Low-power, integrated-optical light switches and low-energy, integrated-optical bistable devices capable of performing optical logic have been demonstrated. It is tempting to propose that such digital optical switching elements be used to construct high-speed computers as well as repeaters and terminal equipment for optical communications systems. A very exciting area of research explores the use of optics to realize a lower cost, smaller size, reduced power, and high speed processors for matrix-vector and matrix-matrix products, polynomial evaluation, partial differential and integral equation solutions, and solutions of sets of linear equations. As continued improvements in electronic speed and power begin to slow, optics will assume a role of increasing importance in our quest to maintain computational superiority in the U.S. over our rivals in both the economic and national security realms.

The major developments that are needed to advance the utility of optical processing fall into the four categories of architectures and algorithms, materials, spatial light modulators (SLMS), and sources and detectors. Over the years, algorithm development has been severely constrained by hardware limitations. For example, image processing operators are local rather than global, two-dimensional signals are computer segmented into a series of one-dimensional signals, and computer architectures are still Von Neumann based. Even the expanding capabilities of VLSI are not being fully exploited because over the past 25 years processing algorithms and architectures have not changed significantly. The digital community has recently been showing interest in parallel processing with advances in data flow architectures and functional level programming; however, a great deal of research and development remains to be accomplished in parallel algorithm formulation if we are to realize a significant improvement in throughput rates. Those researchers having experience with optical architectures may be more visionary toward parallel algorithm concepts than their digital counterparts because of the hands-on experience with parallel devices.

Much of the device work in sources and detectors has been driven by communications requirements rather than by optical processing needs; consequently, the area is dominated by one-dimensional hardware. The parallel computing goal is to achieve one million parallel channels. Therefore, one would ideally like 1000 x 1000 elements source and detector arrays that are compatible with one another and with the SLMs. Source properties requiring improvement include: greater linearity and a larger dynamic range in the current/light-intensity transfer characteristics, on-chip temperature control and drive circuitry, increased uniformity, enhanced modal stability, and longer lifetime. Detector advances should focus on increased linear dynamic range, induced cross-talk, better sensitivity, parallel readout capability, increased speed, and better uniformity. In addition, improved post detection electronics will be needed to handle the high throughput rates which will amount to as much as a billion bits per second on a million parallel channels. This will likely require the capabilities of the silicon VHSIC devices or GaAs microcircuits.

## 2. Technical Objectives

Over the past ten years the Principal Investigator has been active in applying optics to signal processing technology. Of important relevance is the development of a compact, mode-locked semiconductor laser capable of generating picosecond pulses at a multi-GHz repetition rate, tunable in the 0.8 µm - 1.5 µm spectral range. Under this SBIR (Phase I) contract, we have utilized this system as a master oscillator to develop devices capable of signal processing and logic operation that are compatible with the pulse-power and repetition rates available with our mode-locked semiconductor laser. The ultimate objective of this program under Phase II is to demonstrate a prototype system for space qualified service. We envision that the follow-on developmental activity should lead to major accomplishments in the field of communications signal processing, not readily accomplished otherwise.

The basic operating principle of the multiplexer/demultiplexer and XOR gate described here is the nonlinear interaction of modes in optical waveguides. The accomplishments outlined here are centered around the feasibility of such interactions with the ultimate objective of producing a prototype realization of a multiplexer and XOR gate (in Phase II) operating at rates of the order of 50 GHz and with pulse energies of less than 1 pjoule.

## 3.0 Optical Logic Devices

Optical logic devices have stirred the inventor's imagination ever since bistable optical semiconductor devices were proposed to perform logic operations. For such operations, a source of short pulses compatible with integrated optics was necessary. Such a source was not available. The semiconductor laser was not a cw device at that time, and attempts at producing reproducible short pulses from semiconductor lasers proved fruitless.

With the invention of this compact semiconductor laser in the external cavity by the Principal Investigator, there is a great opportunity to re-open the investigation of optical logic devices with the purpose of achieving signal processing rates not achievable by electronic means. If lasers are to be the sources of optical pulses, one must confine the search for devices to those that can be energized with the limited energies available from semiconductor lasers operating typically at 1 mW with pulses at a duty ration of ~ 10 and 10 psec in width. This gives a pulse energy of 0.10 picojoules. Also, the device has to recover within the time between two successive logic operations.

### 3.1 Optical Logic Using Nonlinear Semiconductor Waveguides

A logic device is an inherently nonlinear device. Nonlinearities may be of the resistive type or reactive type. Among the former is saturable gain and/or absorption, among the latter is the piezoelectric effect (a $\chi^{(2)}$ processes) or higher order dielectric nonlinearities ($\chi^{(n)}$ processes). If optical logic devices are to compete successfully with their electronic competitors, they must offer sufficient advantages in speed over electronic devices in order to overcome the many disadvantages associated with signal processing by optical means, i.e, the relatively primitive stage of Integrated Optics Technology, the severe topological constraints imposed by waveguide circuits versus wire circuits, etc.

With this premise one is forced to look at optical logic devices that perform all their operations optically at speeds much higher than those achieved electronically. Of course, optical signal processing devices will produce electronic outputs, but after high-speed pre-processing has reduced the output rate to that compatible with electronic circuits.

Because resistive nonlinearities require excessive intensities, we have chosen to concentrate on reactive nonlinearities. Here, the intensities may be kept relatively low if one accepts processing with delays.

Many studies on waveguides in III-V semiconductors - mainly GaAs - have been reported in the past 12 years, and have encompassed a wide variety of structures (18). Much of this early work concentrated on using carrier concentration variations to produce an appropriate refractive index profile (18-22). In some cases (18-20), localized diffusion or implantation has produced guiding in both vertical and lateral directions. Although this has advantages in ease of fabrication, it does not allow the independent control of vertical and lateral confinement which is very important for optimizing guide performance. As mentioned earlier, the other disadvantage of using carrier concentration variations is the possibility of high absorption loss. The refractive index is only a weak function of carrier density in GaAs and quite high substrate doping densities need to be used ($\approx 10^{18} cm^{-3}$). However, using relatively thick (3.5 μm) $n^-$ epilayers and improved fabrication techniques, propagation losses as low as 2 dB/cm have recently been measured in $n^-n^+$ GaAs waveguides (6). These thick epilayers result in a rather high operating voltage for electro-optically controlled devices. It seems unlikely that devices using carrier concentration variations will give the ultimate in low loss, and they only allow limited flexibility in device design.

With gradually improving control over epitaxial growth techniques, it has become possible to make low loss waveguides using compositional variations to produce the refractive index profile. Single mode GaAs/GaAlAs waveguide structures have been demonstrated using LPE (9) with propagation losses as low as 1 dB/cm at $\lambda$=1.56 μm and similar structures made with MBE-grown material (7) have given losses <2dB/cm at $\lambda$=1.15 μm. MO-CVD has also been used, and multimode waveguides using a GaAs/GaAlAs structure have given losses of 1.4 dB/cm at $\lambda$=+1.3 μm (8). It seems likely that this approach of using compositional variations to provide the necessary refractive index profiles is the best approach for low propagation losses, and allows more flexibility in device design.

The residual losses between 1 and 2 dB/cm measured on these heterostructure waveguides seem likely to be due to scattering from the waveguide edges.

Improvements in waveguide fabrication technology should improve this. Several methods for etching semiconductor rib waveguides have been reported, including wet chemical etching (8), argon ion beam milling (7) and reactive ion etching (6), each with their own advantages and disadvantages.

A significant feature of the chemically etched waveguide is that the chemical used was selective to a specific crystallographic direction, and thus extremely smooth guide walls were obtained. However, one of the disadvantages of chemical etching is that it is not possible to maintain this mesa shape around a curve - and curves are particularly important in many waveguide devices. The ion-beam milling technique is a very well controlled process giving high yields. Curved guides can be formed readily with no change in mesa shape with direction. However, there is a certain edge roughness which is thought to be associated with the photoresist pattern. Clearly there is considerable scope to improve rib roughness - possibly a combination of dry and wet etching might be optimum.

Besides these rib waveguides using planar epitaxial material, some novel approaches have also been pursued. We have explored a single mode GaAs waveguide with an oxide confining layer made by a technique of lateral epitaxial growth by VPE (23). This has shown a loss of 2.3 dB/cm. An $n/n^+$ GaAs waveguide has also been made by localized epitaxy with a propagation loss of 1.5 dB/cm (24). The unconventional prismatic shapes of these latter guides may limit their applications, especially if electric fields need to be applied.

We have also explored photoelastically induced waveguiding in semiconductors (49, 50). In these structures, (the refractive index is varied by introducing strain by depositing a metal or dielectric layer on the semiconductor.) These waveguides have the advantage of ease of fabrication, and being planar, such guides may be affected less by scattering. However, unlike other techniques, lateral and vertical confinement cannot be controlled independently, and there are uncertainties about the long term behavior of devices which rely on stress effects.

Perhaps a more promising structure for the future is the buried waveguide (27, 28). In this type of structure, the guiding region can be grown in a groove etched in the substrate or epilayers (27) - a technique commonly used for buried heterostructure lasers. Alternatively, the guides may be buried by growing over an etched rib waveguide (28). These techniques, usually requiring two stages of epitaxial growth, are more complex than the simple rib waveguide, and so far the losses have been >5 dB/cm. However, buried guides are expected to give lower scattering losses than those encountered in exposed rib structures, and they are much more compatible with many of the advanced laser structures. Thus they may be more suitable for integration.

For many applications InP-based materials will be preferred - particularly for structures in which lasers and detectors operating in the wavelength range $\lambda$=1.3 - 1.6 µm are integrated. (It should be noted that GaAs-based waveguides will be suitable for $\lambda$=1.3-1.55 µm if sources and detectors do not need to be integrated monolithically ). Waveguides have been made in InP-based material (25-28) but their performance is not yet as good as GaAs waveguides, because the materials technology is not as well advanced.

## 3.2 Other Non-Switchable Waveguides

As well as straight waveguides, other elements of integrated optical circuits have been demonstrated in semiconductors, including Y-junctions, polarizers and curved waveguides.

Y-junctions made with InGaAsP buried guides (28) have shown excess splitting losses varying between 0.2 dB and 3.3 dB as the intersection angle increased from $0.6^{\circ}$ to $3^{\circ}$. Y-junctions have also been made with $n/n^{+}$ InP rib waveguides using chemical etching (29). For an intersection angle of $1^{\circ}$ the excess loss was I dB. This is probably an indication of the extra scattering caused by the rib waveguide. These devices form an essential part of one type of Mach-Zehnder switch, and to reduce further this branching loss, it will be necessary to pay careful attention to the exact shape of the intersection.

Polarizers can be made by loading a waveguide with a metal, when TM modes will absorb preferentially. A 35 dB extinction ratio has been obtained in a 250 µm long rib waveguide structure (30).

The performance of curved waveguides is an area in which the use of semiconductors is particularly beneficial. Because guided modes radiate energy from a curved waveguide, tight confinement in both lateral and vertical directions is required. Using a $Ga_{0.88}Al_{0.12}As/GaAs$ waveguide with a relatively high mesa, a loss of 0.6 dB/radian has been measured on a curved guide with a 300 μm radius of curvature (31). This loss value was thought to have been limited by scattering from edge roughness, rather than radiation due to the bend. The benefits of the strong guiding offered by semiconductors has also been demonstrated by measurements on abrupt bends (28). Using buried InGaAsP/InP waveguides, excess bend losses varied from 0.1 dB at an angle of $0.5^{\circ}$ to 4.2 dB at $3.4^{\circ}$. Because of the relatively small index change induced by Ti indiffusion in $LiNbO_3$, small radii curves and abrupt bends with such low loss are not possible. Curves with a small radius of curvature will be important in achieving high packing densities in optical integrated circuits.

## 3.3 Switchable Devices

Switchable semiconductor devices (using the electro-optic effect) include phase modulators (32), directional couplers (6, 9, 25), Mach-Zehnder interferometer switches (33) and TE-TM mode converters (13). An attempt to summarize the results on recent semiconductor devices is given in Table 1, which also includes some state-of-the-art $LiNbO_3$ devices (18). It can be extremely difficult to make objective comparisons between different devices - not least because there are often trade-offs between various aspects of performance, and sometimes the less favorable parameters are not discussed in the published literature. The figure of merit that has been taken is the voltage for a $\pi$ phase shift x length product normalized to wavelength ($V\pi L/\lambda^2$). The $\lambda^2$ term is introduced because the amount of phase shift depends on wavelength [(eqn (1)]; and the distance over which the electric field is applied is dependent on the mode size, which is also approximately proportional to $\lambda$.

Our examination of Table 1 indicates that the $V\pi L/\lambda^2$ figure of merit for $LiNbO_3$ and semiconductors are not as dissimilar as the 6:1 difference in $n^3r$ might suggest. This is because the optical/electric field overlap can be higher for semiconductors. However, there is still considerable scope for improvement, as the best semiconductor device (32) is not fully optimized. It is clear from Table 1 that semiconductor losses are still significantly higher than those of $LiNbO_3$, and this is the area in which most effort must be directed in the future. The results of references 34 and 36 indicate the trade-offs between various parameters for $LiNbO_3$ devices, in particular between insertion loss and $V_\pi$. With the increased control over electrical and optical fields offered by semiconductor technology, it is hoped that this trade-off will be more favorable in semiconductors.

## TABLE 1
Comparison of Various Electro-Optic Waveguide Devices Made With Different Materials

| Device | Length (mm) | Voltage (V) | Bandwidth (GHz) | Loss | ($\mu$m) | $V\pi L/\lambda^2$ | ext ratio (dB) | ref |
|---|---|---|---|---|---|---|---|---|
| GaAs/GaAlAs | | | | | | | | |
| PM | 4.2 | 9 | >1.2 (est) | 5.5dB/cm | 1.15 | 29 | | 32 |
| DC | 9 | 15 | | 1dB/cm | 1.55 | 55 | 15 | 9 |
| DC | 3.5 | 40 | 3 | 6 - 10dB (L-F) | 1.3 | 83 | 15 | 6 |
| MZ | 2.5 | 25 | 5 (est) | | 1.3 | 37 | 14.5 | 33 |
| MC | 4.9 | 12.5 | | | 1.06 | 55 | 27 | 13 |
| InP | | | | | | | | |
| DC | 6.5 | 12 | | | 1.51 | 34 | 16 | 25 |
| $LiNbO_3$ | | | | | | | | |
| DC | | 16 | 2 | 2dB (F-F) | 1.5 | 64 | 18 | 34 |
| DC | 9 | 11 | 1.5 | 4dB (F-F) | 1.5 | 44 | 21 | 34 |
| DC | 16 | 6 | | 2dB (F-F) | 1.3 | 57 | 27/21 | 35 |
| DC(TW) | 14.5 | 4.5 | 7.5 | 8dB (F-F) | 1.3 | 39 | | 36 |
| DC(TW) | 9.5 | 7.5 | 10.5 | 7dB (F-F) | 1.3 | 42 | | 36 |
| DC(TW) | 19.5 | 4.5 | 5.5 | 2.2dB (F-F) | 1.3 | 52 | | 36 |
| DC(TW) | 9.5 | 18 | 10 | 1.5dB (F-F) | 1.3 | 101 | | 36 |
| MZ | 4 | 4 | 2.75 | | 0.85 | 22 | | 37 |
| MZ(TW) | | 4 | 13.2 | | 0.85 | | | 37 |
| MZ | 3 | 4.5 | | | 0.63 | 33 | 17 | 38 |
| MZ | 6 | 3.8 | 1.1 | | 0.65 | 54 | | 39 |
| MZ(TW) | 4 | 2 | 13 | | 0.84 | 11 | | 47 |
| MC | 5 | 17 | | | 1.35 | 47 | 17 | 11 |

Notes

1) PM=phase modulator; DC=directional coupler; MZ=Mach-Zehnder; MC=TE-TM mode converter; TW=travelling wave electrode configuration.

2) F-F corresponds to a fibre-to-fibre insertion loss measurement. L-F corresponds to a semiconductor laser-to-fibre insertion loss measurement.

## 4. Non-Linear and Bistable Elements

A range of devices employing non-linear processes may be envisaged. In particular, in the same way that the whole of electronics is based on non-linear electronic devices, a similar family of optical devices may eventually have applications.

Non-linear optical effects are caused by the non-linear polarization of the medium through which the optical wave is propagating. Various non-linear effects corresponding to the different order susceptibility terms have been investigated in a variety of materials. Although the second order susceptibility term (responsible for second harmonic generation, parametric oscillation and amplification) can be quite large for semiconductors compared with other materials (40), most of the work on III-V semiconductors has concentrated on the third order susceptibility ($\chi^{(3)}$). This gives rise to an intensity dependent refractive index which is particularly relevant to optical logic applications. Optical bistability may be obtained if a material with an intensity dependent refractive index is placed in a suitably designed Fabry-Perot cavity (41). The value of $\chi^{(3)}$ in III-V semiconductors using wavelengths well away from the bandage (the non-resonant case) is extremely small, and it will not be particularly useful because extremely high powers will be needed, even with the small active volumes offered by waveguide structures. Most of the work on optical bistability has involved working near an absorption resonance. Under these circumstances $\chi^{(3)}$ can be enhanced quite dramatically. Optical bistability associated with resonant effects has been observed in GaAs (42), GaAs/GaAlAs multi-quantum well structures (43), InAs (44), and InSb (45). In the latter material, a range of optical logic elements has been demonstrated including AND and OR gates, and a "transphasor", the optical analogue of a transistor. The power density for operation of some of these inSb devices has been extremely low (10W/cm$^2$ at a temperature <77K). However, InSb is probably not the optimum semiconductor material for optical bistability devices; there are no ternary or quaternary compounds which can be grown expitaxially on InSb for an optimum waveguide structure and/or the integration of other optical and electronic components. In addition, the band-gap is probably too narrow for use at useful wavelengths at room temperature. However, the work on InSb has demonstrated that devices employing optical bistability are certainly feasible.

Whereas the non-linearities in InSb are due to effects associated with transitions between conduction and valence band edges, those in GaAs are thought to be associated with exciton states. The preliminary work on simple GaAlAs/GaAs/GaAlAs etalons showed bistability at low temperatures, but not near room temperature where the exciton binding energy becomes comparable with kT. However, optical bistability has been demonstrated at room temperature in GaAs/GaAlAs superlattices - the exciton binding energy being increased in such structures. Although power densities are quite high ($10^5 W/cm^2$), scaling to waveguide dimensions indicates that power levels will be well within those available from semiconductor lasers. In fact, semiconductors with appropriate focussing have been used to demonstrate optical bistability at room temperature in the superlattice structures (46).

A major problem with the operation of these devices at present is their speed. The $\chi^{(3)}$ - induced optical bistability depends on carrier dynamics, and the turn-off time depends on the carrier recombination time (a few nsec in normal material at room temperature). Although this could be reduced by modifying the material appropriately, e.g., introducing fast recombination centers, the switching power would then be compromised. Indeed, it seems there will be a trade off between switching power and speed, and more work is needed to establish how favorable this is for device operation - especially waveguide devices.

An alternative approach to obtaining bistable effects is to use a hybrid arrangement (51). The optical output from a Fabry-Perot cavity is detected and used to generate a voltage which varies the refractive index within the cavity by the electro-optic effect. This sort of feedback system allows a non-linear light input/light output relationship, hysteresis and optical bistability. The electronics can have gain, so very little power is needed to demonstrate optical bistability, and the cavity medium need not have an intensity dependent refractive index. The speed of such devices is limited by that of the electronics. As one of the major benefits of optical logic is its potential for ultra-high speed, this hybrid approach may not be the most attractive option in the long term. The ability to integrate all the optical and electronic elements on one chip could, however, be very useful.

## 5. Picosecond Pulse Techniques

### 5.1 Pulse generation

There has been considerable interest in generating very short optical pulses, either as a repetitive sequence, or 'on demand' (i.e., with variable pulse separation), for a wide variety of applications including fast, optical signal processing, picosecond spectroscopy, sampling and optical communications. Semiconductor lasers have been used in a variety of configurations to produce such pulses as outlined in Table 2 and can have the merits of compactness, easy operation, high repetition rates (many GHz), tunability and a wide range of wavelengths. Most of the work to date has focussed on demonstrating and understanding the techniques. We have demonstrated a variety of basic methods of producing picosecond pulses using semiconductors, and have explored various aspects of integrating picosecond pulses with other components.

The main methods of obtaining short pulses using semiconductors are summarized (18) in Table 2. The simplest of these is to drive the laser with a short but intense current pulse which rapidly raises the carrier concentration from well below threshold to well above it. The output power builds up rapidly until it starts to deplete the carriers and thus reduce the gain. If the drive pulse is terminated at this stage, a short high power optical pulse is obtained; if the drive pulse is continued, the damped relaxation oscillation transient characteristics typical of injection lasers will be obtained. This method of 'gain switching' a laser has been demonstrated with both GaAlAs and InGaAsP lasers, using avalanche transistors, step recovery diodes and rf drives. Pulses as short as 15 ps have been obtained, and shorter pulses predicted (53). For methods where the electrical pulses are available on demand, the optical pulses will also be available on demand - although some patterning will arise for pulses closer than the recombination time (a few ns). The output pulse of such lasers is spectrally impure, having many longitudinal modes, but this can be overcome by using external cavity mode selection methods such as a grating (54) or possibly by switching a DFB laser. The ultimate aim would be for Fourier transform limited linewidth products. One of the advantages of such gain switching is the very high peak powers that can be obtained (80 - 20,000 mW), although it is unlikely that mean powers would exceed typical cw laser power capabilities.

TABLE 2

Different Methods of Obtaining Picosecond Pulses From Semiconductors

| | pulse width (ps) | limit (ps) | pulse rate (Hz) | Comments |
|---|---|---|---|---|
| 1 Gain switching<br>- pulsed<br>- sinusoidal | 5 - 30<br>30 | $\tau_{ph}$<br>(2L/c) | single—$2\times10^9$<br>$10^8$ — $10^{10}$ | Simple, on demand pulses, multimode or single mode |
| 2 Optically pumped gain switching | 1 | $\tau_{ph}$ | $\simeq 10^9$ | Very short cavity (few $\mu$m) usually with high reflectivity, tunable using thickness variation. |
| 3 Q switching (i.e. loss switching) | $\simeq 14$ | $\tau_{ph}$ | $3\times10^9$ — $1.2\times10^{10}$ | Loss and gain regions may be integrated, on demand, high power pulses. |
| 4 Modelocking<br>- active<br>- passive | 5.3<br><br>.56 | $\frac{1}{(gainwidth)}$<br>sub psec | | Periodic, needs high quality ext cavity (very good ar coatings), integrated external cavity demonstrated. |
| 5 Self pulsation | 20 - 100 | | $10^8$ - $10^9$ | Poorly understood and uncontrollable. |
| 6 Optically switched cw optical input | 19 | | $10^9$ - $10^{11}$ | Conceptually very easy to integrate, low peak power. |

The gain switching may also be obtained by optical excitation, and this method has been investigated extensively with platelet or film lasers in which a thin layer of semiconductor (2-20 μm thick) is placed between two reflectors and excited by picosecond optical pulses from a mode-locked non-semiconductor laser. The gain width can be very broad (several kT), but with only one Fabry-Perot mode falling within this gain width, single longitudinal mode emission is obtained. By using wedge shaped samples, the wavelength of the mode can be tuned over the whole gain width (55), and by using the appropriate bandgap semiconductor, a very wide range of wavelengths may be produced.

In the Q switched method (56), a gain and switchable loss mechanism is incorporated within the cavity. The gain region is driven hard to a large value of gain, but lasing is prevented by the lossy region. If this loss is now decreased, a lasing pulse will build up very rapidly. This pulse will terminate itself by the rapid depletion of the gain. The loss region should return to a high loss state before the gain can build up. Both the gain and loss regions have been integrated on the same chip (63) by using split electrode configurations. Pulses of <40 ps (detector limited) at a repetition rate of 14GHz were obtained using an InGaAsP/InP structure. Peak powers of several hundred milliwatts should be obtained using this method.

In active mode locking (57) a semiconductor laser with one perfectly anti-reflection coated facet is placed in an external cavity. The laser is modulated with a sinusoidal rf or pulse train having a modulation period equal to the photon round trip time ($t_r$). The emitted pulses see gain on arrival at the laser, and the peak sees the highest gain, thus sharpening the pulse.

This pulse actually consists of many external cavity modes locked in phase, and the Fourier transform of such a composite waveform is a train of pulses of width approximately $t_r/N$ and period $t_r$ - N is the number of modes locked together. With a typical gain width of 100 nm at 1.55 μm, pulses as short as 30 fs could, in principle, be generated if modelocking occurs over the whole spectrum. In practice, unwanted sub-cavity modes and, ultimately, dispersion prevent this.

Bandwidth limited ($\Delta\tau\times\Delta\nu=0.36$) pulses of 16 ps have been obtained (58). The external cavity needs to be quite long (several cm) to allow conveniently low pulse frequencies, and in one case (65) a SELFOC resonator has been used as the cavity. Active modelocking using semiconductor lasers has also been demonstrated by driving the laser cw and using an optical switch within the external cavity. Using an InGaAsP/InP laser with a $LiNbO_3$ travelling-wave modulator, pulses of 22 ps have been generated at 7.2 GHz (36).

In passive modelocking, a laser with a region of saturable absorption is placed in an external cavity and driven with a dc bias only. Although the mechanism is not completely understood yet, the evolution of picosecond pulses can be considered as follows (59); if the light intensity exceeds a critical value it can saturate the absorber so that the most intense light sees gain on both passes through the semiconductor. The gain will become depleted, thus truncating the light pulse, but the absorber bleaches more rapidly than the gain depletes providing a short period of net gain. This process will continue during each round trip with the pulse gaining in amplitude but shrinking in width until it is limited by dispersion. Van der Ziel (59) obtained 0.65 ps pulses, which was consistent with dispersion limitations. These broadened to 20 ps bandwidth limited pulses when an etalon was introduced. The exact properties of the saturable absorber are rather important, and most of the work seems to have been carried out with degraded or damaged semiconductor material. However, by using a semiconductor laser with a split electrode configuration (64) the amount of saturable absorption may be controlled reasonably well.

There has been a large number of publications describing lasers which unintentionally produce sub-nanosecond pulse trains at rates between 0.1 and 1 GHz when driven with a dc current. There are probably several different ways in which this behavior could arise, e.g., saturable absorbers, deep traps or non-uniform excitation in the active layer. As, at present, these effects are uncontrolled, they will not be considered as useful sources of picosecond pulses.

Picosecond pulses can also be obtained by optically modulating the output of a cw laser. Using a comb-generator driven interferometric travelling-wave $LiNbO_3$ modulator, pulses of 45 ps have been achieved (60), and 47 ps has been demonstrated using a $LiNbO_3$ travelling-wave directional coupler (66). Using a standing wave resonator to avoid the limitations set by the differing microwave and optical propagation velocities in $LiNbO_3$, pulses of 19 ps at 20 GHz have been produced (67). However, being a resonant structure, this type of device will only operate within a small range of pulse frequencies near the resonance. As mentioned earlier, semiconductor, travelling wave devices may allow higher repetition rates and shorter pulses. Short pulses can also be generated by overdriving optical modulators (61, 62) but all these methods have the disadvantage of dissipating the unwanted energy. Thus, the output energy per pulse is likely to be rather small.

It is clear that there are several methods of obtaining pulses from 0.5 to 50 ps from semiconductor devices at frequencies of $10^5$ to $10^{10}$ Hz. Some of these methods, in particular, modelocking, Q switching and gain switching, are capable of high peak powers which will be useful for non-linear applications. Although these methods are useful for providing discrete optical pulse generators, their usefulness, particularly for optical logic, picosecond sampling and optical communications will be considerably enhanced with monolithic integration. In principle, lasers may be integrated either by using on-chip facet techniques, or by using gratings, so it should be possible to realize these pulse generators in integrated form. The integration of techniques 1, 3, 5 and 6 in Table 2 is conceptually easy, but for modelocking a relatively long external cavity is required, together with some form of bandwidth restriction. One approach would be to use a DFB laser, which would act as the source and a method of controlling the bandwidth, with an integrated low loss waveguide as the cavity. A long cavity will be needed if relatively low pulse repetition rates are required (5 cm in a semiconductor corresponds to a repetition rate of about 1 GHz). Long waveguides may be realized using curved sections to increase the packing density. Clearly there will be considerably less problems at the higher bit rates where cavity lengths may be shorter. Dispersion could be the dominant limitation to short pulses in such structures.

## 6. Ultra Compact Tunable Mode-Locked Diode Lasers for Optical Time Division Multiplexing and Demultiplexing

During the Phase I of this SBIR Program we demonstrated the first optically pumped MQW laser. In Phase II Program we plan to use several of these MQW samples as saturable absorbers for our studies. The MQW absorber consists of 68 periods of 100 GaAs layers alternated with 102 of $Ga_{0.72}Al_{0.28}As$ layers grown by molecular beam epitaxy on top of a 1µm $Ga_{0.72}Al_{0.28}As$ etch-stop layer on a GaAs substrate. This sample will be epoxied to a high reflectivity dielectric mirror on a sapphire substrate, and the GaAs will be removed by a selective etch. The exposed surface of the MQW absorber will be anti-reflective coated. The unsaturated reflectivity of the mirror-MQW assembly is 0.25 at the peak of the exciton resonance (846 nm), and it increases to ~0.5 at the pulse power levels in the laser resonator under mode-locking conditions.

### 6.1 MQW Lasers Developed During Phase I

For the purpose of our studies under Phase II, we plan to utilize a compact mode-locked semiconductor diode laser capable of emitting trains of very short (~1 psec) optical pulses. The development of such a source is ideal for future pulse-modulated high speed optical communication systems. During the past few years we have extensively studied (102-113) the physical principles involved in mode-locking these lasers. One fundamental problem for passive mode-locking has been the identification and characterization of a suitable saturable-absorber element. GaAs/GaAlAs multiple quantum well (MQW) structure has proven to be one such saturable-absorber element (114) for passive mode-locking of a diode laser in an external cavity.

We have currently assembled a state-of-the-art mode-locked diode laser as illustrated in Figure 1. The commercial GaAs laser diode (Hitachi HLP-1400) is utilized as a pump source. We have made a slight modification to this laser by anti-reflection coating one facet of the diode and mounting the diode on a special V-groove microstage designed by TACAN engineers (patent is pending).

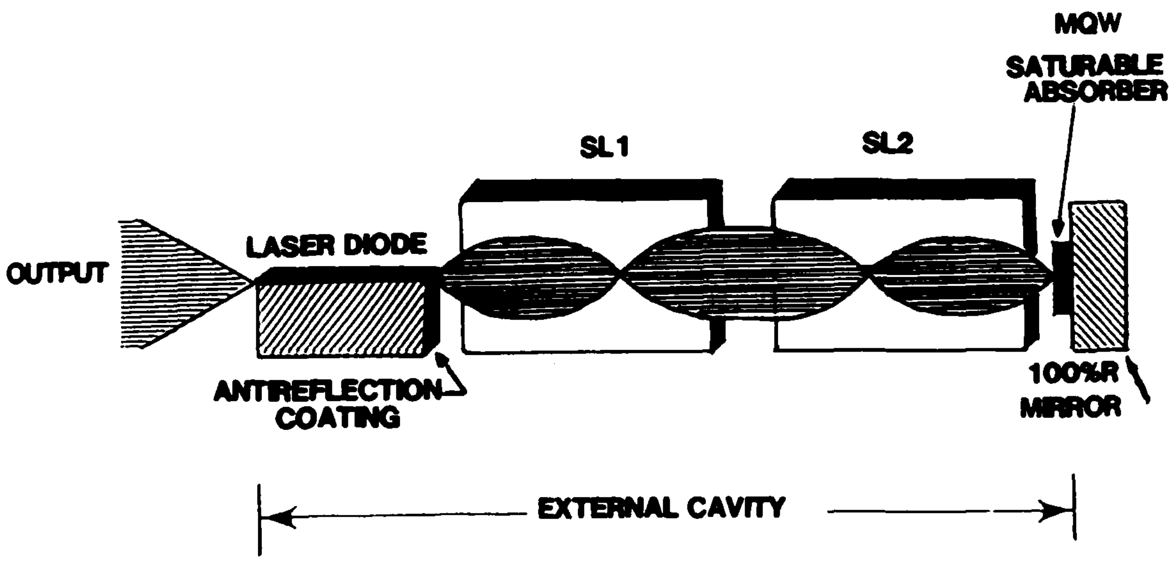



FIGURE 1. Mode-Locked Diode Laser

The output of the diode laser was coupled to a self-focusing (selfoc) microlens ($SL_1$). The self-focusing microlens has several advantages: mechanical rigidity, insensitivity to environmental fluctuations, high numerical aperature, and output beam aspect ratio of near unity.

Light from $Sl_1$ is coupled into a second selfoc lens ($SL_2$), which is used to focus the light onto the MQW absorber to a spot radius of ~1 µm. The total length of the external cavity is ~30 cm corresponding to a pulse repetition rate of 1 GHz. We have obtained stable mode-locked pulses at currents near the laser threshold. Pulses as short as 2 psec have been observed with an average output power of ~2 mW with a repetition rate of 1 GHz.

The implications of using an ultra compact all solid-state picosecond device for the purpose of optical bistable systems is tremendous. We have demonstrated (115) tunability over wide spectral range by making a small change in the selfoc lens-MQW absorber spacing using a chromatic aberration of the lens-prism combination. In addition, MQW material shows a great promise for practical application of bistable optical devices. Since the above MQW external cavity picosecond laser system is utilizing a commercially available diode laser as the active gain media, its compatibility with MQW as a practical signal processing element should lead to important developments in devices and essential elements in optical systems of the future.

### 6.2. Application to a Optical Time-Division Multiplexer

In order to demonstrate the compatibility of this mode-locked diode laser with optical signal processing elements, we will examine its utilization as a highly repetitive picosecond light source in a high speed optical time-division multiplexer (or demultiplexer) that might be used to multiplex picosecond optical pulses into a high capacity optical fiber, and demultiplex the signals at the receiver to obtain low enough bit rates to allow handling by optical detectors and subsequent electronic systems.

A multiplexer can be made from a number of triggerable switching elements (51), as shown in Figure 2a. A trigger pulse with the proper time synchronization is required to multiplex pulses as shown. Each element could be made from a properly designed bistable optical device, as shown in Figure 2b. Our bistable device consists of MQW material with a very large nonlinearity at room temperature.

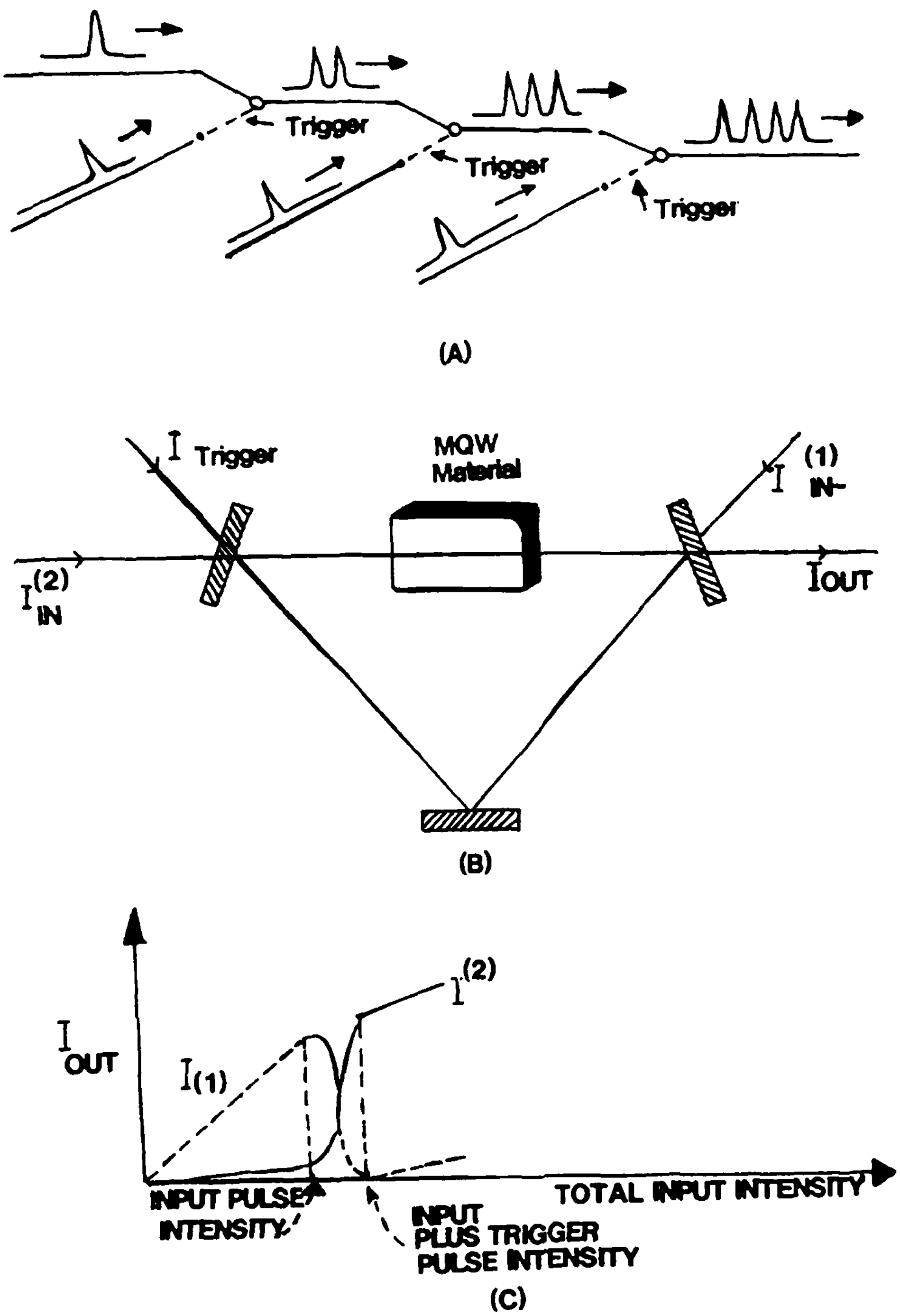



FIGURE 2. Optical Time-Division Demultiplexer.

(A) Overall Schematic Diagram

(B) Ring Triggerable Bistable Element

(C) Output Characteristic of Ring Bistable Element

Currently, we are planning to place such a bistable MQW material in a ring resonator (108). The ring geometry allows separation of the inputs and outputs. However, some polarization selectivity may have to be employed to avoid interference effects between the two input beams $I_{IN}^{(1)}$ and $I_{IN}^{(2)}$. Let us assume here that pulses in these two beams are never present simultaneously in the element. The output intensity depends on the total input intensity $I_{IN}^{(1)} + I_{IN}^{(2)} + I_{TRIG}$ as shown in Figure 2c. If the input pulses are of intensity slightly less than the critical intensity corresponding to the "knee" of the curves, the output in the absence of a trigger input will consist solely of $I_{IN}^{(1)}$. However, during the time that a small trigger signal $I_{TRIG}$ is present, the output will consist solely of $I_{IN}^{(2)}$. Because of the sharp "knee" in the characteristic curves, only a small $I_{TRIG}$ is required to accomplish this switching.

## 6.3 Applications to Optical-Time Division Demultiplexer

In a similar way, one can perform demultiplexing (51) by using an optical "tap", as shown in Figure 3a. A similar bistable ring resonator serves as a triggerable "tap", as shown in Figure 3b; the output characteristics are shown in Figure 3c. MQW may well be an appropriate nonlinear material for use in these devices because of a very large and sharp room temperature nonlinearity near the MQW excitonic resonances. By using our mode-locked diode laser at $\lambda \sim 8400$ we should be able to obtain a sufficiently large nonlinearity to allow the device to operate at a pulse power level of about 1.3 mW with a time response of $\sim 1$ ps. The technology of semiconductor diode lasers and MQW materials for optical signal processing is a very dynamic one in which there appears to be a tremendous potential for rapid growth.

## 7. Multiplexer and Demultiplexer

We have examined an integrated optical version of a microwave driven phase-matched multiplexer and demultiplexer capable of combining and separating in an efficient way two pulse trains from a mode-locked semiconductor diode laser. The design is shown in Figure 4.

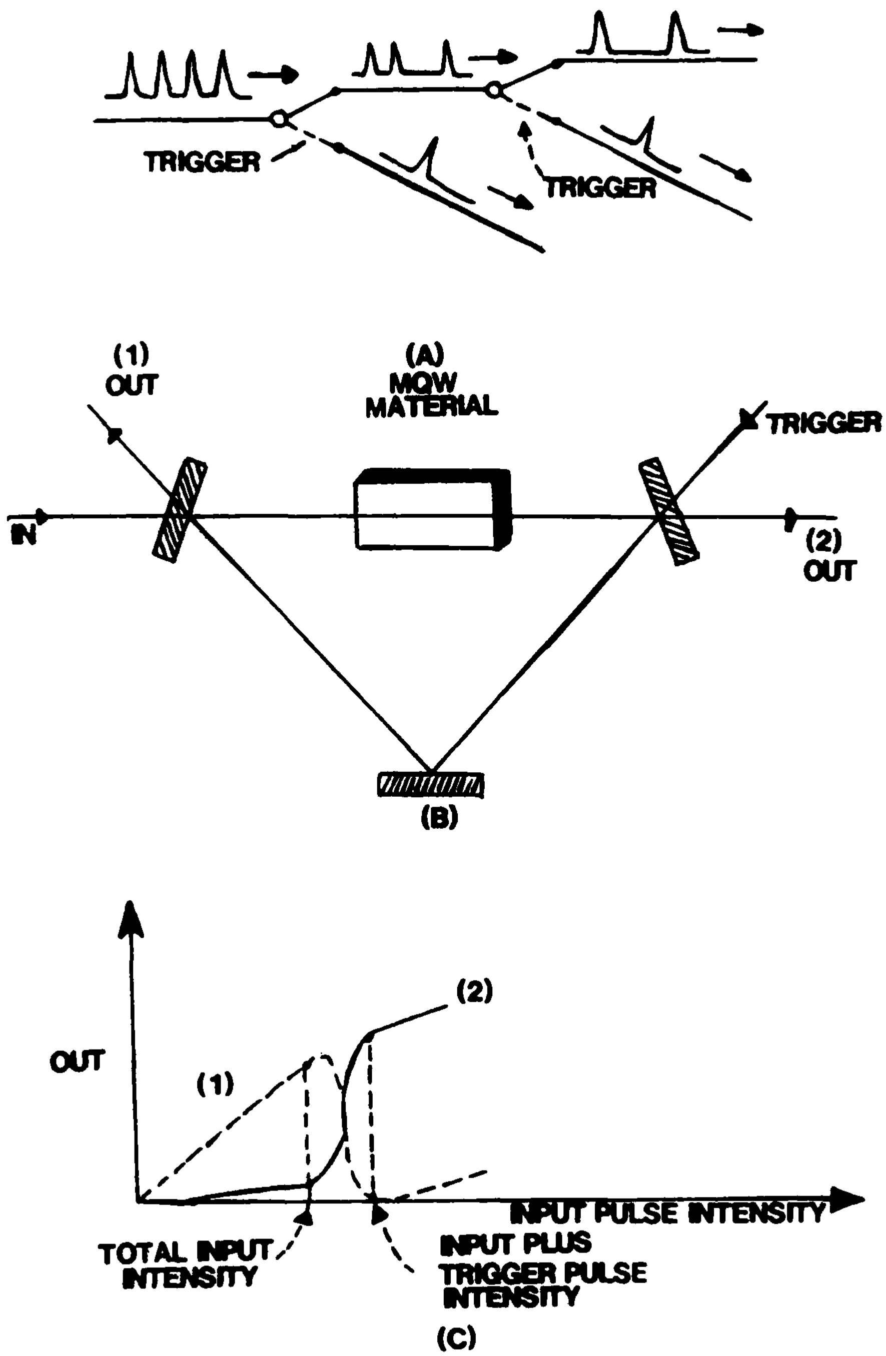



FIGURE 3. Optical Time-Division Demultiplexer

(A) Overall Schematic Diagram

(B) Ring Triggerable Bistable Element

(C) Output Characteristic of Ring Bistable Element

Our task is to couple two optical guides that approach each other in the "coupling region". The coupling is effected by a dc voltage $V_o$ and a microwave signal of peak voltage $V_\mu$ traveling synchronously with the optical pulse train. The voltages are so adjusted that with $V_o + V_\mu$ applied, synchronism is produced; with $V_o - V_\mu$ applied, the phase velocity of one guide is changed from that of the other guide. A pulse that travels with the crest of the wave is coupled from guide 1 to guide 2 (or from guide 2 to guide 1) within the total travel length of the coupler. A pulse traveling within the trough of the wave remains in its respective waveguide. An additional electrode is provided so that the phase velocity in guide 2 can be "fine-tuned". The high x material (such as $Ba_2Ti_9O_{20}$ multiple quantum well) on top of the microstrip line will be adjusted so that the $\mu$ wave phase velocity is made equal to the optical phase velocity. While only single frequency matching of the microwave impedances is required, it is necessary to match each end of the waveguide separately so as to avoid high standing waves inside the device. This could be done using time domain reflectometry.

Figure 4 shows a multiplexer in GaAlAs. An alternate design could be based on InGaAsP. A design where the guidance is obtained by the action of the metal on the surface (18) of the GaAs is shown in Figure 5. In this case the microwaves may be launched in a balanced configuration from a coaxial line.

It is clear that a standing wave at the microwave frequency can be used instead of a traveling wave (18). The traveling optical field interacts with one of the two traveling waves. The traveling optical field interacts with one of the two traveling wave components making up the standing wave. Further, it is clear that a standing wave pattern can be simulated artificially by a push-pull microwave driven electrode structure. If the spacing of the electrodes is S, then the fundamental "propagation" constant is $\pi/S$ and the phase velocity is $v = \omega S/\pi$. This v must be made equal to the group velocity of the optical pulses. The net result will be that the microwave field traveling synchronously with an optical field in a pair of coupled waveguides causes transfer of a pulse from one guide to another if the pulse is in phase with the peak of the microwave field, and no transfer if it is in opposite phase.

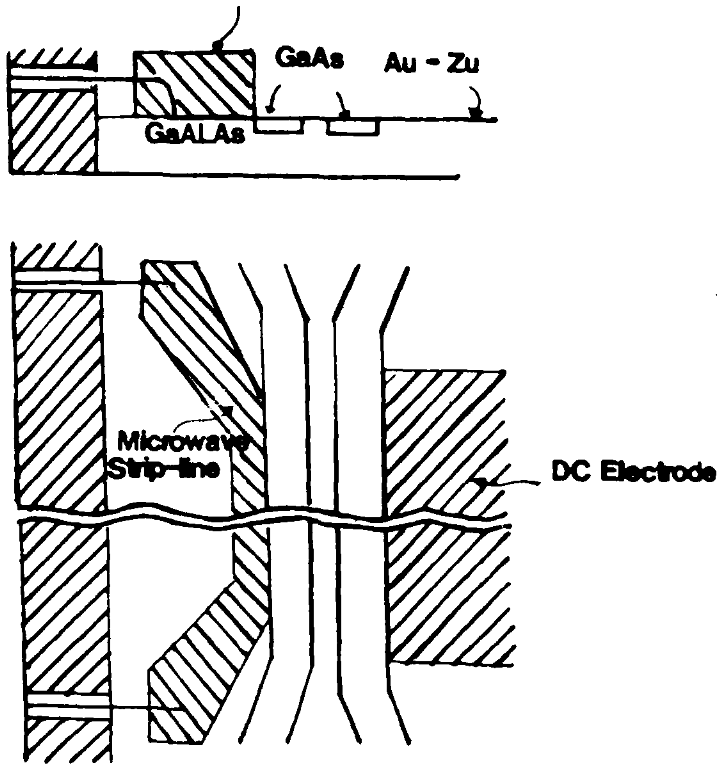



FIGURE 4. Multiplexer

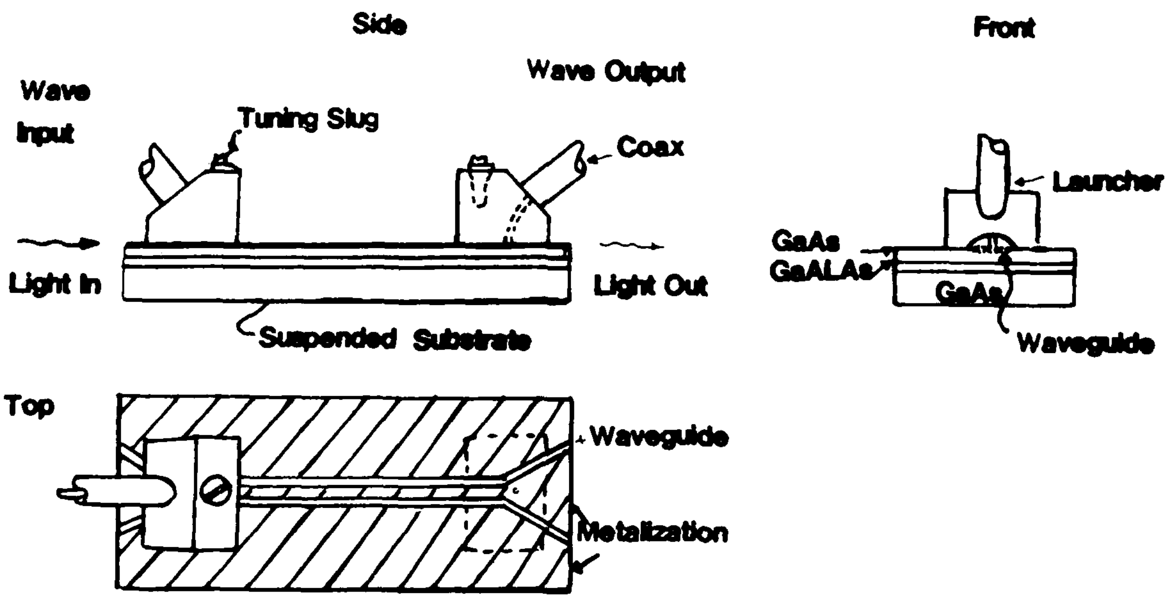



FIGURE 5. Multiplexer Based on Metal Gap Guides

## 8. Logic Elements Compatible With Picosecond Semiconductor Sources

With existing technology, one can build electronically operated optical switches that would operate at a 3 GHz rate. Therefore, it is feasible to modulate one pulse-train emitted from the semiconductor diode laser. To obtain high processing rates, one has to multiplex many of such modulated pulse trains into one single sequence of pulses (116). Figure 6 shows the schematic of such a system. The pulses emitted from a semiconductor laser are separated by a set of waveguide couplers that are indicated schematically as beam splitters in Figure 6. Each pulse-train passes through a modulator and all of them are combined in a multiplexer to produce a single modulated pulse-train in the common output waveguide.

Typically, a mode-locked laser delivers 1 mW with a duty cycle of 10. The peak power is thus 10 mW. The guide cross section is of the order of 10 $\mu m^2$, the intensity is $10^6$ watts/cm$^2$. We have demonstrated that powers of this order of magnitude can convert efficiently from a fundamental to a second harmonic under phase matched conditions within guides of 1 cm length using available electro-optic $\chi^{(2)}$ materials, e.g., $LiIO_3$. We propose a nonlinear optical system that operates either as an inverter, XOR gate or AND gate using a waveguide containing $\chi^{(2)}$ material. The scheme uses solely one nonlinear element--all other elements are linear mode-couplers and mode selectors. Other variations on the theme replace the waveguide mode selector by frequency shifting and filtering. We start by discussing this simplest system.

Figure 7 shows a schematic of this nonlinear optical system (120-121). Pulse trains to be processed enter in channels (a) and (s), respectively. Pulse train (a) is in an antisymmetric waveguide mode (as indicated schematically), pulse train (s) is in a symmetric mode. In the 3 db coupler, the two modes are combined in a single waveguide. This waveguide feeds into a $\chi^{(2)}$ waveguide filled with a $\chi^{(2)}$ crystal. The polarization, $P_i = \chi_{ijk} E_j E_k$, produced by the product of the two fields $E_j E_k$, will have a symmetric pattern (along $x_l$) when $E_j$ and $E_k$ are both antisymmetric or symmetric. The propagation constants of the antisymmetric and symmetric modes at frequency $\omega$ are denoted by $k_a(\omega)$ and $k_s(\omega)$. We may prevent the second harmonic from being produced by phase-mismatching the symmetric modes at frequency $2\omega$, with propagation constants $k_s^{(i)}(2\omega)$, from both $2k_a(\omega)$ and $2k_s(\omega)$. By phase-matching the lowest antisymmetric mode of propagation constant $k_a(2\omega)$ so that $k_a(\omega) + k_s(\omega) = k_a(2\omega)$, one produces a strong second harmonic in the $\chi^{(2)}$ waveguide if, and only if, $E_j^s(\omega)$ and $E_k^a(\omega)$ are present simultaneously. Radiation in one mode uses up the other. If the waveguide is long enough, the radiation $E_j^s(\omega)$ and $E_k^A(\omega)$ can be made negligibly small.

In this manner one may realize different logic operations depending upon what output is being used; i.e.; inverter, XOR-gate, AND-gate, or a symmetric to asymmetric mode converter or summation of (S) and (a) modes (120). These alternatives are briefly discussed below.

## 8.1 Inverter

If the pulse train (a) consists of a continuous sequence of pulses, then the output "port" detects the antisymmetric mode at frequency $\omega$. Therefore, the system operates as an inverter of the signal in port (s). The presence of a pulse in (s) destroys a pulse in (a), the absence of a pulse in (s) allows the passage through the system of a pulse in (a).

## 8.2 XOR-Gate

We now input signals in channels (a) and (s). The output is the sum of the outputs in (s) and (a) at frequency $\omega$. The response will occur only when there is a pulse in (a) or in (s), but not in both or not when there is no pulse in either input channel.

## 8.3 AND-Gate

If one inputs signals in both channels (a) and (s), and picks up the second harmonic in the output, one obtains a signal if, and only if, there is a pulse present in both channels. This corresponds to an AND-Gate operation. Clearly, the output has to be converted back to $\omega$ to complete the operation. This can be done in an $\chi^{(2)}$ crystal via mixing with a cw signal at $\omega$. An AND operation can, of course, be performed by a combination of XOR and Inverter gates without requiring a frequency shift.

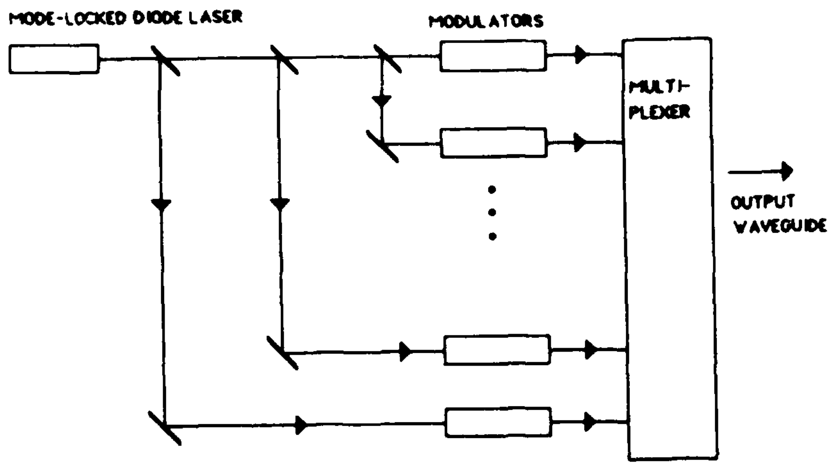
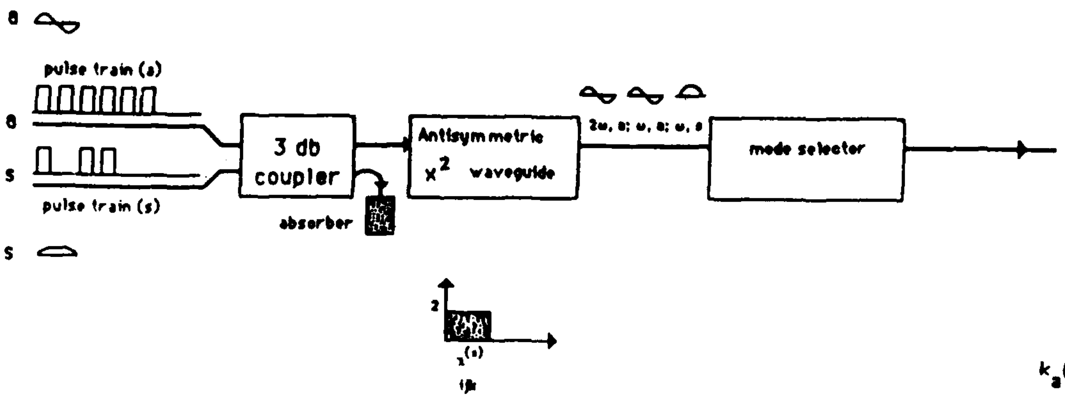



FIGURE 6. Multiplexer with Several Modulator Pulse Trains




$$k_a(\omega) + k_s(\omega) = k_s(2\omega)$$

(i) Inverter: Train (a) is uniform sequence "mode selector" selects $2\omega$,s.

$$2K_a(\omega) = k_a(2\omega)$$

(ii) XOR Gate: Train (a) and (b) are both signals. "Mode selector" selects $\omega$, s and $\omega$, a.

$$2k_s(\omega) = k_a(2\omega)$$

FIGURE 7. Nonlinear System of Pulse Train Processing

## 8.4 Symmetric to Asymmetric Mode Converter

The logic devices discussed here utilize symmetric and antisymmetric modes, and coupling among them. Consider the two optical waveguides in Figure 8 with overlapping fringing fields (120-121). The dispersion relation for the two guides is shown in the inset. A mode launched in the (s) guide couples to the a-mode in the (a) guide because the guide dimensions are adjusted so that $k_a = k_s$. The length of the guides is such that $\kappa L = \pi/2$, where $\kappa$ is the coupling coefficient in the coupling of modes formalism. After full transfer has occurred, the (s) guide may be terminated (in a match in order to suppress residual reflections).

## 8.5 Summation of (s) and (a) Modes

In the output of the XOR-gate system, both (s) and (a) modes appear. To get a standard signal we must convert to a superposition of (s) modes. This can be done in two steps: couple the (a) mode to an adjacent waveguide s-mode, and couple the s-mode to the (s) mode of another adjacent waveguide. Now both signals are in separate s-mode waveguides. The signals may be recombined in a 3 db coupler.

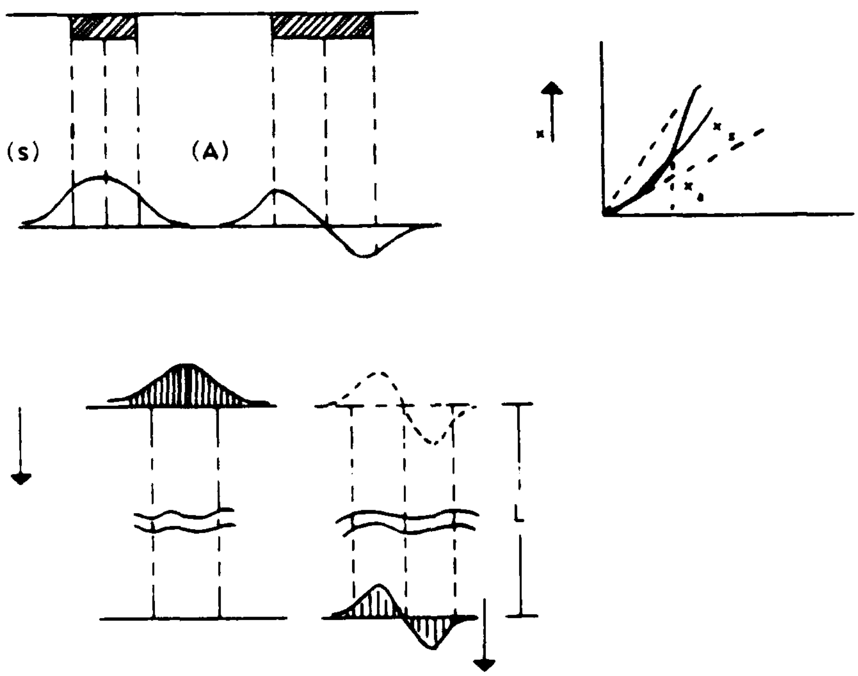



FIGURE 8. Optical Waveguides with Overlapping Fringing Fields Dispersion Relation (Inset)

## 8.6 An Alternate Realization of an AND-Gate

The mode selectors may be replaced by frequency selectors if one is willing to use the additional nonlinear operations of frequency shifting (118). Figure 9 shows an optical AND-gate constructed in this way (120-121).

Two pulse trains to be operated upon are shown schematically in the incoming optical waveguides. One of the two pulse trains is frequency shifted by an amount of $\delta\omega$. The choice of $\delta\omega$ is dictated by the availability of optical filters as explained further on. The two pulse trains are combined into a single waveguide in a multiplexer. Then the combined pulse train passes through an $\chi^{(2)}$ waveguide with the phase matching condition, $k(\omega) + k(\omega + \delta\omega) = k(2\omega + \delta\omega)$. In this manner, a signal is produced at $2\omega + \delta\omega$ if, and only if, input pulses were present in both channels. The output of the $\chi^{(2)}$ waveguide is filtered in a passband filter passing $2\omega + \delta\omega$ and rejecting $\omega$, $\omega + \delta\omega$, $2\omega$ and $2\omega + 2\delta\omega$. After that, the resulting signal is down converted to $\omega$, giving an AND.

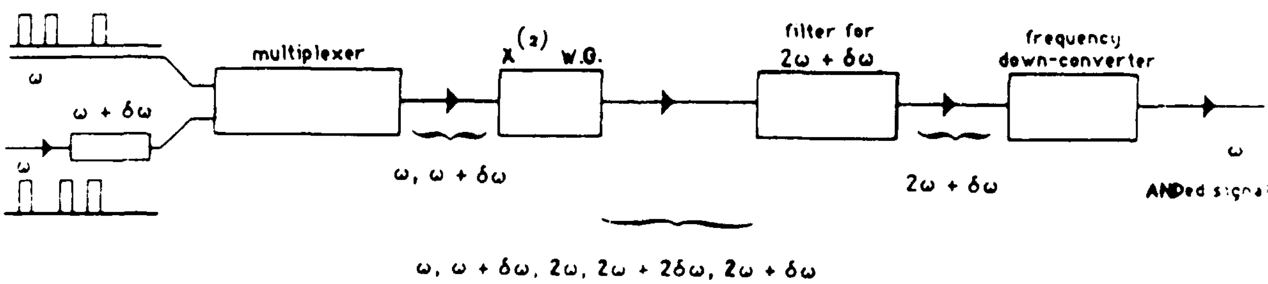



FIGURE 9. Optical AND-Gate Using Frequency Selectors

Such optical logic devices, based on picosecond optical inputs, not only circumvent problems related to the coupling of high-speed signals to and from the GaAs chip (and the related problems of parasitics and loading), but also provide an unambiguous determination of the gate delay (in contrast with the conventional ring oscillator and Gigahertz rate "divide-by-two" techniques). Numerous variations of these optical techniques will be implemented in our laboratories for the direct measurement of on-chip propagation delays and waveforms in Gigahertz logic circuits with unprecedented (~ 10 ps) resolution and accuracy.

From a long-term perspective, the optical addressing of logic circuits--particularly with compact semiconductor lasers that may be integrable with semiconductor chips containing the ICs themselves--also has several important applications in future high-speed data processors. For instance, current speed bottlenecks in high-speed computers may be alleviated with the use of hybrid electro-optical data processors, in which data transmission between various points on high-density integrated circuits would occur via ultrashort light pulses and imaging holographic interconnections. The potential of such concepts for novel designs of computer architecture will be explored in the follow-on developmental activity in Phase II leading to service test hardware for space-qualified applications.

## 9. Ultra-High Speed Detection

As well as ultra-high optical pulse generation, it may be necessary to convert ultra-fast optical pulses to electrical pulses in a semiconductor integrated optical circuit. Ideally, of course, it would be desirable to avoid completely the need for high speed electrical pulses - i.e. the various optical processing stages should ultimately provide an electrical output at a low speed which could be handled relatively easily. Indeed, the transmission of picosecond electrical pulses without crosstalk and other forms of corruption is a major problem in its own right, and one of the reasons why optics is so attractive for high speed applications. It would appear, however, that elements for detecting picosecond optical pulses will not be as difficult to make as those to provide the pulses in the first place, and their integration should be relatively easy.

The most studied detector for ultra-fast pulses is the photoconductor. The speed of these devices is determined by the carrier lifetime, which is influenced by recombination in the bulk or at interfaces, surfaces or contacts. Photoconductors can show gain, and thus high responsivities, but the methods of reducing lifetime often employed, (e.g., proton damage), usually reduce the mobility and thus the gain. This might not be a problem for many applications, but could be important if the incident optical power is limited, such as in telecommunications applications. In principle, however, it should be possible to combine a short lifetime with a reasonable mobility, and this must be a technological challenge for the future. Fast photoconductive detectors have been made in GaAs (68), and InP (69), with response times typically less than 50 ps.

This approach is particularly attractive, because a photoconductor is an extremely simple structure (merely an optically-sensitive resistor), and it should be possible to integrate these with great ease. However, other detectors may be suitable. In particular, a GaAs Schottky device with a response time of 5.4 ps and bandwidth of 100 GHz has been demonstrated (70) and InGaAs/InP PIN diodes have shown response times of 30 ps (71). These devices are more complex than the photoconductor, and require epitaxial layers. However, they may give advantages in responsivity and sensitivity.

## 10. Novel Quantum Well Structures

The development of MBE (molecular beam epitaxy) and MO-VPE (metallorganic vapor phase epitaxy) which can controllably produce very uniform multilayer structures of thicknesses from a few atomic layers to several microns, has allowed the fabrication of several novel structures which are likely to facilitate the development of optical circuits.

The quantum well (QW) structure (72) consists of a narrow bandgap layer sandwiched between wider bandgap layers, the narrow layer having a thickness less than the de Broglie length (≈100), so that carriers are confined to two-dimensional motion. This results in the density of allowed states becoming a staircase function, bounded by the parabolic curve for bulk material. This, and other differences, influence a large number of the fundamental properties of the material such as the gain and absorption spectra, transport properties and various non-linear effects. Often, many quantum wells are stacked together (multi quantum wells, MQWs) to enhance these effects.

A variant on the MQW is the strained layer superlattice (SLS) (73). In conventional epitaxy, all the layers are usually grown lattice-matched to the substrate to prevent strain and dislocations. In strained layer superlattices, the restriction that all the layers must be lattice-matched is relaxed, but the layer thicknesses and mismatches are controlled so that the overall strain is minimized or nulled such that the individual strains are kept below the critical value at which defect formation would occur. SLSs are often, but not always, MQWs, and thus have all their benefits, but additionally offer a greater degree of flexibility on the choice of compositions that may be grown on a given substrate. Perhaps more significantly, they add an extra degree of freedom which could be used to optimize the properties of the effective band structure of the composite material. Details of the conduction band and valence band edge might be changed, and also effective masses and thus transport properties. Additionally, the band structure can become sufficiently distorted by the local strain, so that direct bandgap superlattices can be made using indirect bandgap constituents (e.g., GaAsP on GaP) (74).

QW structures in GaAlAs/GaAs have already been used to demonstrate lasers with reduced threshold currents (75), reduced and thickness controlled lasing wavelengths (77), sharper gain spectra (76), and are expected to show other benefits (78-80). However, because of the effects of non-radiative recombination, particularly Auger recombination (81), it is not clear yet how many of these benefits will transfer to other materials systems, particularly those for longer wavelength applications, where Auger recombination is more important. The enhanced gain in MQW lasers will allow reduced current operation, thus lower thermal dissipation, and will allow the possibility of integrating a large number of lasers on one chip. Threshold currents of only a few mA have already been demonstrated, and further reductions are possible. Another major benefit of MQW structures is enhanced non-linear effects. This has been demonstrated in our laboratories as reported in the second progress report.

Superlattices in which there are periodic doping, rather than compositional variations, [the nipi superlattice (82)], offer a new range of tunable properties including optical gain (83). The tunability, and the fact that the gain operates below the band edge, could result in a simpler technology for integrating lasers and waveguides, as well as matching emission wavelengths to particular resonances for non-linear devices, or in matching local oscillator and signal oscillator frequencies for coherent optical systems (84).

Thin epilayers have also allowed the development of new electronic devices, for example, the use of two-dimensional electron gas in the high electron mobility transistor (HEMT) (85). This should benefit integrated optics because of its improved integrability and performance.

## 11. Integration

Semiconductor, optical-integrated circuits offer the possibility not only of a wide range of optical processing functions, but also opto-electronic and electronic devices on the same chip. The technology to realize these concepts appears formidable at present, but progress is rapid, and a start at demonstrating limited degrees of integration has been made (18).

To date, the passive and electro-optic features have only been developed to the 'building block' phase. More advanced components such as star couplers, matrix switches, A-D converters and others as demonstrated in $LiNbO_3$ have not been made in semiconductors yet, although with recent improvements in epitaxial techniques and the fabrication of relatively low-loss, low voltage waveguide devices recently, progress could be rapid. In many cases a single epitaxial layer structure could be used, perhaps a variant on Figure C-1, Appendix C, but with slight processing variations for different devices [e.g. the curved output guides of a rib waveguide directional coupler may require extra etching to increase confinement (17)].

The inclusion of a laser on the chip considerably increases its usefulness. Discrete semiconductor lasers have cleaved facets acting as mirrors, and this is not really compatible with integration. However, there are other methods for making semiconductor lasers which do not involve conventional cleaving, and some of these are more suited to integration.

(i) Etched facets. High quality facets have been obtained using etching techniques (86), but there will always be problems in coupling the output from an etched facet laser to a monolithically integrated optical waveguide. Fresnel reflections are the main difficulty, - reflection loss will limit the coupling efficiency, and the reflected light will cause spectral fluctuations. However, when a laser needs to be coupled to an external guide (fiber), or when a low coupling efficiency can be tolerated in an integrated circuit (e.g. coupling to a monitor photodetector) etched facets may be useful.

(ii) Micro-cleaved facets. In this technique, the active layer is exposed as a cantilever by selective etching, and then removed ultrasonically. Very low threshold current lasers have been obtained by this method (87). They have the same features as etched facet lasers for monolithic coupling to waveguides.

(iii) Ring laser (88). In principle this is a integrable laser, but it requires an output coupler. The problem of achieving a ring structure with sufficiently small radius of curvature (<100$\mu$m) such that threshold currents are low together with achieving low radiation loss from the curved waveguide is a major limitation to this method.

(iv) Distributed Feedback (DFB) laser (89). In this device a grating is incorporated in or near the active region of the laser; this acts as a distributed reflector and mirrors are not required. Although the technology for making these complex devices (the grating period needs to be of the order of 0.25 µm) is becoming reasonably well established, a difficulty arises if one wants to integrate the laser with a waveguide. This is because the laser active region, although transparent when pumped, is absorbing outside the gain region. Thus a more complex structure is needed. Figure 10 shows a simple approach in which the basic three layer DFB structure is grown, prior to etching and subsequent growth of a p Inp layer (18) over the whole structure. The InGaAsP laser confining layer becomes the waveguide layer, and proton isolation could be used to isolate electrically the waveguide from the laser. In this simple structure, the overlap between the optical fields is not optimum, but improved structures may be envisaged - although they will require even more complex epitaxial growth.

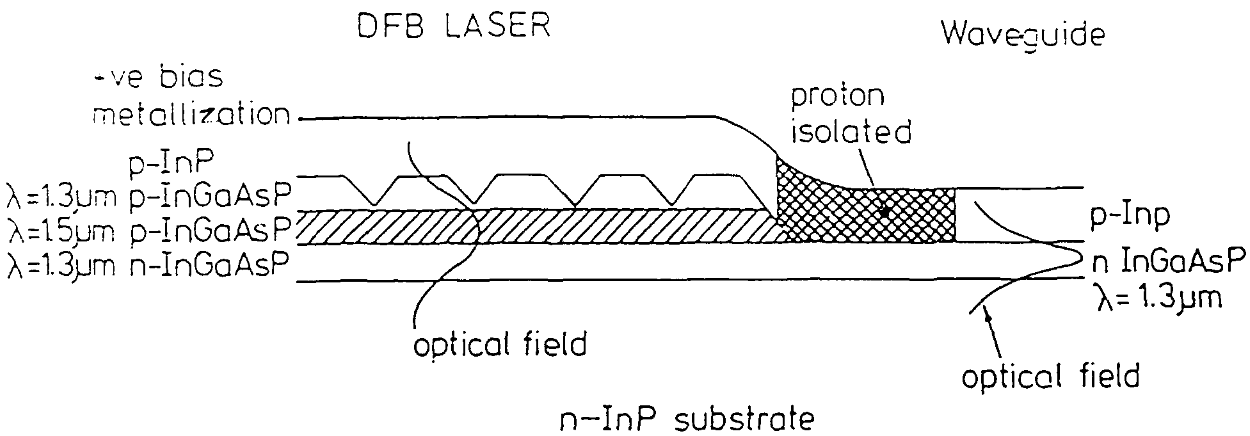



FIGURE 10

A Scheme For Integrating a DFB Laser With a Waveguide

(v) Distributed Bragg Reflector (DBR) (90). The structure can be similar to the DFB, but the gratings are positioned outside the gain region in the waveguide layers.

It is the latter two techniques that have received most attention - devices with gratings incorporated have advantages as discrete devices because they operate with a single longitudinal mode. The DFB is probably the easiest to make - and can also be considerably shorter.

Aiki, et al (91) integrated six GaAlAs/GaAs DFB lasers of different wavelengths onto a single chip, using waveguides to combine the signals into one output waveguide. The overall efficiency was poor, but this is the most ambitious demonstration of the integrated optics concept. Mertz, et al (92) have coupled etched-facet lasers to detectors via straight and curved waveguides, and although losses were once again rather high, these circuits do demonstrate the feasibility of such integration, and with improved designs and fabrication techniques, better performance should be possible.

Although there has been limited work on the integration of lasers and waveguides, there has been very significant progress in integrating electronic devices with lasers. In one approach, the electronic devices are incorporated adjacent to the laser stripe within the cleaved facets. For example, Bar-Chaim, et al (93) have integrated a photodiode, a FET and a laser on a semi-insulating GaAs substrate to produce a rudimentary optical repeater with a gain bandwidth product of 178 MHz, and they predict improvements to better than 1 GHz. Much of this type of work has employed LPE, but larger circuits will need the improved control of MBE and/or MO-VPE, and improved circuit planarity. Sanada, et al (94) used MBE on channelled substrates to obtain nearly planar laser/FET circuits. They also used MQW active layers to reduce chip thermal dissipation, and achieved a conversion ration of laser output to FET gate voltage of 3.3 mW/V with rise and fall times of 1 ns.

The restrictions imposed by working within the confines of the laser facets are removed by using integrable lasers, and both Matsueda, et al (95) and Carney et al (96) describe optoelectronic integrated circuits using such lasers grown in recessed parts of the substrate, in order to improve the planarity for subsequent GaAs IC processing steps. Carney et al describe their development of a transmitter consisting of a laser, drive circuit and 4x1 multiplexer capable of 1 Gbit/s operation, although, at that time, the circuit was not fully operational. The integration of a PIN photodiode and high performance FET is very useful, and progress on both GaAs/GaAs and InGaAs/InP devices has been made (97,98). In the case of the GaAs receivers, a useful transimpedance preamplifier has been integrated with the PIN diode (99). It is clear that quite complex GaAs-based optoelectronic circuits are becoming available at the research stage already, and that the preliminary steps for the 1.3-1.6 μm region are progressing rapidly.

Figure 11 shows an example of the optoelectronic integrated circuit (OEIC) concept (100). This particular component would take a number of optical inputs, convert the signals to electrical form, and perform various switching operations before reconverting to optical signals again. It is envisaged that such a device will be extremely useful for optical communications especially in local area networks and local network distribution schemes. Of course, this is not a true optical circuit as all the processing occurs in electronic form, but with suitable developments in technology, the switching could be done in optical form, which would confer advantages for some applications.

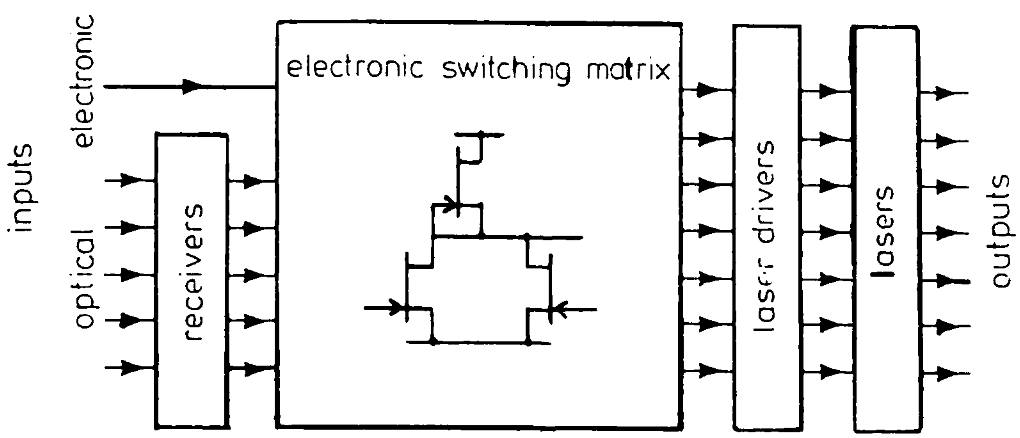



FIGURE 11. An Optoelectronic Integrated Circuit (OEIC)

The rapid progress in integration of electronic circuits with lasers and detectors has been due principally to the use of improved epitaxial growth methods for depositing the optoelectronic device layers. Progress has clearly been most rapid in GaAs-based circuits where the existing GaAs IC technology may be used directly. However, the benefits of integration for InP-based optoelectronic integrated circuits are large, and an increasing number of laboratories are establishing the techniques needed. Progress on integrating waveguides on the other hand has been slow, partly because of the availability of $LiNbO_3$ devices as an alternative to semiconductors, but also because of lack of suitable material. Now that this is becoming available, and as improved discrete devices are being demonstrated, the waveguide integration is likely to accelerate. The use of waveguide techniques in coherent communication applications would result in highly practical and high performance systems.

## 12. Other Semiconductor Growth and Processing Technology

The development of suitable epitaxial growth techniques is crucial for the realization of the advanced electronic and optical devices mentioned in this paper. The most widely used epitaxial technique for III-V semiconductors is liquid phase epitaxy (LPE), but it is generally held that this will not be the most suitable for waveguides, and the more advanced optical and electrical devices. This is primarily because a large area of material with a sufficiently low defect density is hard to obtain. However, some of the best waveguide devices to date have been achieved using LPE (6,9,13).

The techniques on which hopes are based are MO-VPE and MBE. In principle, these techniques should give large areas of material with well controlled composition and thickness. Both MO-VPE and MBE have demonstrated good GaAs/GaAlAs laser structures. Waveguides have also been made out of GaAs-based material grown by these techniques, but further development is needed before optimum structures can be obtained routinely. One limitation at present seems to be doping control - in particular the demonstration of low-doped ($<10^{15}cm^{-3}$) GaAlAs layers. The growth of InP-based materials is at a very rudimentary stage. Although there is considerable work world-wide on adapting the MO-VPE and NBE techniques to InGaAsP and InGaAlAs, LPE is still the only option at present for InP-based heterostructure devices.

Thus it seems that in the immediate future, LPE is likely to be used widely to demonstrate discrete waveguides and the simplest waveguide structures, but that over the next few years MO-VPE and MBE will emerge as the most suitable techniques, allowing much larger scale integration.

In the demonstrations to date of electronic/optical and optical/optical integrated devices, non-optimum epitaxial layer structures have been employed. For example, a heterojunction bipolar transistor has a similar layer structure to that of a semiconductor laser, so that by compromising the performance of both devices, a single layer structure will allow the monolithic integration of both devices. This is inherently unsatisfactory as the resulting performance can be so inferior as to negate the advantages of integration. In the future it will be desirable to grow optimized structures on different parts of the substrate. This could be done by localized area epitaxy. For example, MBE is ideally suited for in-situ shadow masking. For MO-VPE, it may be necessary to use dielectric masking. Alternatively, the use of an epitaxial photodeposition technique may give improved resolution. Here, an ultra-violet laser is used to stimulate growth, either by localized heating or chemical dissociation.

An important implication of these ideas is the requirement to be able to grow on processed and structured substrates. In many growth techniques for conventional structures, the surface of the substrate is etched away immediately prior to growth to give a good, clean surface for nucleation. This might be unacceptable when growing over certain small features, and there will need to be a much greater understanding of the surfaces of semiconductors, and the requirement for good growth.

Concerning advances in device fabrication, the subject of etching has already been raised. It is likely that semiconductor etching will always be important in the fabrication of integrated optical circuits, although such techniques as epitaxial growth through slots etched in dielectric layers may be envisaged. Dry etching processes are likely to become important because of their uniformity, controllability, and high yield. III-V semiconductors have been etched using ion beam milling, plasma etching, reactive ion etching and reactive ion beam etching, but these techniques need much more development, and a greater understanding of the basic processes involved. The topics of particular importance for integrated optics include uniformity over large areas, anisotropic etching, material selective etching and damage effects.

Lithography is extremely important for waveguide devices. Smooth features (on a <0.1 µm scale) and the ability to replicate patterns over a large area will be more important than very narrow linwidth features. The relative benefits of electron-beam lithography, and the more conventional photolithography will need to be assessed.

A final point worth considering is the incorporation of non-semiconductor materials on semiconductor substrates. Clearly the relatively small electro-optic coefficient of conventional semiconductors and dielectrics is a disadvantage, and various organic materials with much higher electro-optic coefficients and other non-linearities are being studied (101) and may eventually be deposited on semiconductors to allow the combination of optimum materials.

## 13. Future Directions

The ideas presented here are conceived as a result of some exciting investigations made in our laboratories at TACAN Corporation and are based upon the following five important parameters which we have extensively investigated over the past six years:

a. Speed. With an electronic nonlinearity or free carrier generation in semiconductors, subpicosecond switching times are possible.

b. Bandwidth. With a resonant bistable optical device or a nonlinear interface, a large fraction of the visible light bandwidth can be used.

c. The ability to treat directly signals already in the form of light.

d. The capability for parallel processing.

e. Most importantly, the availability of novel nonlinear optical materials at room temperature compatible with diode laser power and wavelength characteristics (ex: *multiple quantum well materials*) suggest possible ideal combinations of properties for these devices. A detailed comparison between semiconductors and $LiNbO_3$ has indicated that semiconductor waveguide device performance should eventually be comparable with that of $LiNbO_3$ in many respects. In particular, the 6:1 difference in the electro-optic figure of merit is offset by the greater ability to achieve good overlaps between optical and electrical fields. Also, although propagation losses are still higher in semiconductor guides, there have been considerable improvements recently, and there appear no fundamental reasons why comparable losses should not eventually be achieved. $LiNbO_3$ will probably always be superior for acousto-optic applications, but there are grounds for believing that semiconductors will ultimately give higher speed performance.

A considerable advantage for $LiNbO_3$ is the availability of large area starting material and relatively easy fabrication techniques (118). It remains to be seen whether semiconductor epitaxial growth and processing technology can be developed sufficiently to produce components of comparable cost. Stability and reliability problems may hamper the implementation of $LiNbO_3$ devices for some applications.

The advantages of semiconductors that may outweigh minor performance or cost differentials is the ability to integrate a variety of electronic and optical devices on one chip. The development of epitaxial growth techniques has allowed the demonstration of a wide range of novel devices in III-V semiconductors, some of which have already been integrated together in small scale circuits. So far, most of the attention has focused on optoelectronic integration, ie lasers, detectors and electronic circuitry. The wider incorporation of waveguides in optical circuits is expected in the near future as growth techniques such as MO-VPE and MBE reach maturity. Semiconductor picosecond optical sources and detectors have been demonstrated in discrete form, and optical bistability has been observed. The possibilities for integrating these devices are promising, bringing the prospect of all-optical logic much closer.

The successful implementation of Phase I of this SBIR program reported here will have an important impact on Phase II of this research effort to utilize TACAN's fabrication facilities for the construction of practical devices whose detailed characteristic were developed under Phase I. We note that there are wonderful opportunities to utilize unique attributes and performance characteristics of all optical systems. Over the course of the past four years, we have performed novel experiments whereby extremely valuable information has been obtained on ultra fast processes in a wide range of semiconductor material. Correspondingly, we have committed ourselves to a major investment in fabrication facilities and material preparation for integrated optical signal processing system. These developments invite a concerted effort toward the identification and utilization of solid-state materials with potentially novel properties. There is a certain analogy of the emergence of microwaves in instrumentation communication to the state-of-the-art roughly thirty years ago. An opportunity exists for bringing these different efforts together with the purpose of breaking ground for a new era of fundamental development in optical signal processing which would lead to the invention of new integrated optical devices for high data rate transmission and fast detectors, among other things. The ideas explored here are based upon the utilization of existing facilities and materials (including multiple quantum well, $LiNbO_3$, $BaTiO_3$, $LiIO_3$ and BSO) in our laboratories. Thus, Phase II should lead to a major developmental activity for fieldable compact service test hardware.

Ultimately, we will use these devices, techniques and processes, reported here, exploring their full potential use and applications in ultra high data rate optical signal processing, telecommunications, and imaging sensors and devices. Because of the emergence of room temperature nonlinear optical materials and their compatibility with low power diode sources, the characteristics of large bandwidth and high speed, and the ability to process signals already in the form of light (which has been demonstrated in our laboratories) has created a surge of interest in its full utilization in optical signal processing elements. Certainly, immunity from electromagnetic interference, better resistance to corrosive and high temperature environments, and above all, the inherent compatibility with diode lasers and fiber optic secure communication links should provide other important applications of our studies to Air Force programs.

14. <u>Personnel</u>

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3. Dr. Kennet Vilhelmsson, Research Physicist
4. Dr. Ernest Kim, Electro-Optical Engineer
5. Dr. Dennis Toms, Research Physicist
6. Mr. Thomas Call, Mechanical Design Engineer
7. Mr. Walter Ganz, Micro-Electronic/VLSI Engineer
8. Mr. David Olson, Laser Technician
9. Mr. Craig Green, Fiber-Optic Technician
10. Mr. Richard Attaway, Fiber-Optic Technician
11. Mr. Larry Mason, Laser Technician
12. Mr. Gary Leibitzke, Micro-Electronic/VLSI Technician

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APPENDIX A

## 1. Material Requirements

The advantage of using optics for certain signal processing applications are well established. Perhaps the best known example is rf spectrum analysis (1) which can be performed at much higher speeds using optics than electronic methods. Another example where optics could offer much higher speeds is in analog-to-digital conversion (2). In addition, with the increasing use of optics in telecommunications, both for long and short haul applications, more and more optical processing functions are being required. For example, the more advanced optical systems in the future may require amplitude, phase and frequency modulation, wavelength and time division multiplexing and and space switching.

At present the processing of optical signals, either using discrete or integrated components, is usually carried out with dielectric materials, most commonly lithium niobate ($LiNbO_3$). This has the particular advantage that suitable starting material is available, and the fabrication of waveguides for optical devices is relatively easy - in general a titanium diffusion is all that is needed to produce the necessary refractive index profiles. Acousto-optic and electro-optic coefficients are reasonably high and the optical propagation loss of $LiNbO_3$ is sufficiently low that, combined with relatively well developed techniques for coupling to and from optical fibers, acceptably low insertion loss can be achieved.

III-V semiconductors - typically gallium arsenide (GaAs) and indium phosphide (InP) - also exhibit acousto-optic and electro-optic effects and can perform many of the optical processing functions demonstrated in dielectrics. For reasons which we will discuss later, III-V semiconductors have not been used widely for acousto-optic applications, and the majority of work on semiconductor waveguide devices has employed the electro-optic effect. The main attraction of using semiconductors is the potential for integrating optical sources, detectors, and any electronic components that are necessary on the same substrate, with all the benefits in performance, size, reliability and cost that this would entail. The particular disadvantages of semiconductors most often quoted are that:

a. they have a relatively low electro-optic coefficient compared with $LiNbO_3$,

b. their measured optical propagation losses have been considerably higher than those in $LiNbO_3$,

c. the growth of suitable epitaxial layers is difficult, and requires expensive equipment.

We have investigated a range of semiconductor waveguide devices and they will be reported here. These are mainly discrete devices (e.g. directional coupler switches, TE-TM mode converters & c) and semiconductor components of the complexity of some of the $LiNbO_3$ devices now being made have not been demonstrated yet. However, recent improvements in semiconductor waveguide performance suggest that it is now feasible to consider the fabrication of larger scale structures (122, 123, 124).

With the development of advanced epitaxial growth techniques such as metallorganic vapor phase epitaxy (MO-VPE) and molecular beam epitaxy (MBE), a variety of novel optical and electronic devices are being realized. The concept of "bandgap engineering" is extending the possibilities for semiconductor device functions, and conventionally accepted limitations to semiconductor device performance are constantly being eroded. While many of these developments are at a very early stage - for discrete devices, let alone integrated structures - the huge potential for semiconductor optoelectronics cannot be ignored. Some of the most interesting of recent developments in III-V semiconductor devices are also discussed in this paper, as well as the status of the monolithic integration of some of the relatively simple structures. The development of semiconductor growth and processing technology is crucial to continuing advances in the field, and this Phase I herewith concludes with some comments on the developments that will be needed in Phase II.

APPENDIX B

## 1. Principles of Semiconductor Waveguides

A variety of semiconductor waveguide structures has been demonstrated. Some of these were explored in Phase I where the essential elements of a semiconductor waveguide were studied with respect to a rib waveguide; probably the most commonly used structure (Figure B-1).

As in any waveguide structure, an appropriate refractive index profile is required. In Figure B-1 the guiding layer (GaAs) is bounded in the vertical direction by a layer of $Ga_{0.96}Al_{0.04}As$ and air. The refractive index difference between GaAs and $Ga_{1-x}Al_xAs$ is approximately 0.4x. The dimensions shown in Figure B-1 are typical for monomode operation.

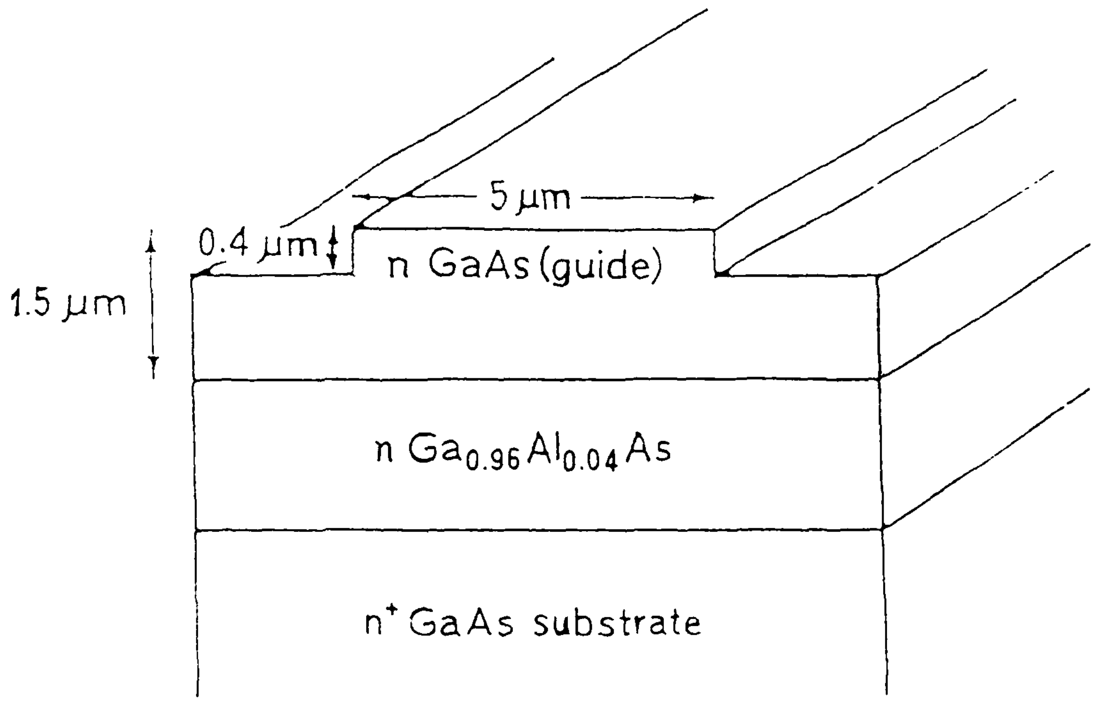


Figure B-1. A GaAs/GaAlAs Rib Waveguide

In the lateral direction, the confinement is obtained by etching a rib structure in the semiconductor. In many cases it will be necessary to apply an electric field to the guiding region, and this can be done with a Schottky contact, obtained by having an appropriate metal layer on top of the rib. An ohmic contract would be applied at the base of the substrate.

APPENDIX C

1. The Properties of Semiconductors Relevant to Waveguide Devices

## 2.1 Electro-optic coefficient

The figure of merit for many waveguide devices is related to the change in propagation constant that can be induced by an electric field (18), for example:

$$\Delta\beta = \pi n^3 r E' L/\lambda \qquad \text{Eq. (1)}$$

where n is the effective refractive index of the waveguide for the propagating mode, r is the electro-optic tensor element appropriate to the crystal orientation and the direction of the applied electric field and L is the device length. E' is an 'effective' electric field, determined by the applied voltage (V), the separation of the electrodes (d) and a factor ($\Gamma$) giving the overlap between the optical ($E_{opt}$) and electric ($E_{elec}$) fields.

The figure of merit most often quoted is $N^3r$. $LiNbO_3$ belongs to the 3m point-group symmetry, and has four non-identical electro-optic coefficients. By using a suitably orientated substrate and electric field direction, the optimum element ($r_{33}$) can be used with $n^3 r_{33} \propto 328 \times 10^{-12}$ m/V. The other elements, $r_{22}$, $r_{13}$ and $r_{51}$ give smaller figures of merit. For GaAs, which has only one coefficient ($r_{41}$), the figure of merit is about 6 times less ($n^3 r_{41} \propto 60 \times 10^{-12}$ m/V) and InP shows a similar value (3). There seems no particular reason to suppose that related III-V ternary and quaternary compounds should be significantly different.

A parameter which is perhaps more useful than $n^3r$ is the voltage length product for a $\pi$ phase shift ($V \pi L$). Taking $E' = V\Gamma/d$, then

$$V\pi L = \lambda d/n^3 r\Gamma \qquad \text{Eq. (2)}$$

This is a particularly relevant parameter because it incorporates the degree of overlap between optical and electrical fields, and it should be minimized for low voltage operation.

The overlap factor $\Gamma$ can be controlled to a limited degree in $LiNbO_3$ by adjusting electrode separations and varying the guide refractive index profile to optimize the overlap. Values of $\Gamma$ less than 0.5 are normally obtained, and values can be considerably less than this if the device is required to have high speed and/or low coupling loss.

With semiconductors there is more scope to optimize $\Gamma$ because the optical and electric field profiles may be controlled independently. The optical field distribution is determined by compositional changes, while the electric field distribution depends on the doping profile. This point can be illustrated with reference to Figure C-1.

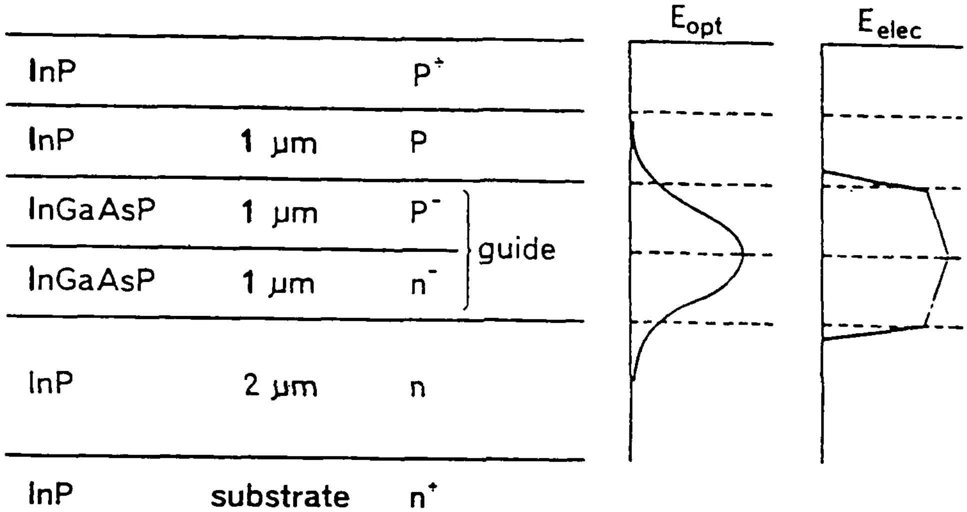


Figure C-1. Possible Slab Waveguide Structure

The waveguiding region consists of a $p^-/n^-$ junction of $In_{1-x}Ga_xAs_yP_{1-y}$. For a 2 μm thick guiding region the value of the refractive index step ($\Delta N$) needed for monomode guiding in this symmetric waveguide structure is about .006 at a wavelength of 1.3 μm. For $InP/In_{1-x}Ga_xAs_yP_{1-y}$ $\Delta N \simeq 0.3y$ and as $y \simeq 2.2x$ for lattice-matching to InP, the composition of the guiding layers should be $In_{0.99}Ga_{0.01}As_{0.02}P_{0.98}$. (It is assumed that the doping levels are sufficiently low that the free carrier contribution to the refractive index can be ignored.)

Adjustments to the layer thickness and composition could give optimized coupling. The electric field profile however, is determined by the applied voltage and the doping profile. In the case that $P \approx 10p^{-}$ and $n \approx 10n^{-}$, most of the voltage will be dropped over the guiding region, and the electric field profile will be as Figure 2. If, however the doping varied gradually through the structure it could, in principle, be possible to engineer a perfect overlap between the electric and optical fields. It is envisaged that the ability to vary the doping in this manner will become available with the development of MO-VPE and MBE. Semiconductor technology is not yet sufficiently advanced to be able to make such optimized structures, but in Section 4 it will be mentioned that the use of double heterostructure waveguides with appropriate doping profiles has already enabled the demonstration of semiconductor devices with $V\pi L$ products comparable with those of good $LiNbO_3$ devices.

## 2.2 Transmission Loss

The transmission loss of a waveguide can be extremely important, especially in applications such as telecommunications where optical power is at a premium. For other applications loss may not be too much of a problem. However, it is clear that the high losses shown by semiconductors to date have been viewed as a major disadvantage.

GaAs/GaAlAs and InP/InGaAsP-based waveguide devices cannot be used for wavelengths <0.8 μm because of band-edge absorption. It may be possible to extend this wavelength range in the future by using other III-V semiconductors, but at present it is more realistic to consider semiconductors solely for applications with $\lambda > 0.85$ μm.

Transmission loss can be separated into two components - propagation losses and coupling loss. In semiconductor waveguides the wavelength of the propagating radiation usually corresponds to a photon energy considerably less than the bandgap energy. Under these circumstances, free-carrier absorption is expected to be the dominant absorption mechanism. This includes inter- and intra-conduction and valence band transitions. The free-carrier absorption coefficient is directly proportional to the number of free carriers. Measurements on bulk

GaAs (4) give a loss of about 13dB/cm at a wavelength between 1 and 1.5 µm for an electron density of $5\times10^{17}cm^{-3}$. This explains why so many of the devices made with an $n^+$ substrate (typically $>10^{18}cm^{-3}$) near the guiding region show such high losses. Bulk InP shows a lower loss -7dB/cm at $10^{18}cm^{-3}$ at a wavelength of 1.3 µm (5) - due to its different band parameters, but the best way of decreasing free carrier absorption losses is to reduce the number of free carriers. There have been no published reports of free-carrier absorption values in bulk material with low doping in the wavelength region of interest, but by extrapolation from published figures the free-carrier absorption is expected to be negligible at electron concentrations less than $10^{16}cm^{-3}$ (4,5). Hole concentrations will need to be much lower because of inter-valence band transitions.

Recently, propagation losses between 1 and 2 dB/cm have been reported for devices with relatively low doping levels (6-9), and it is thought that these values may be limited by scattering from the rough edges of the rib structure that is used to confine the radiation in the lateral direction. Improved methods of rib fabrication, possibly involving such techniques as reactive-ion etching, the use of planar waveguide structures and the growth of epitaxial layers over a rib structure should reduce this scattering loss.

There is still some way to go to achieve acceptably low propagation losses. (0.5 dB/cm might be acceptable initially for discrete devices, but losses may have to be less than this for larger scale integrated circuits.)

The indications to date are that there are no inherent barriers to achieving these figures, and that with improved epitaxial growth (notably lower doping levels), and better fabrication techniques (smoother rib waveguides, buried waveguides) the values demonstrated in $LiNbO_3$ [0.3 dB/cm for single mode waveguides at 1.3 µm; 0.1dB/cm in bulk material at 1.15 µm (10)] should be realized in semiconductors in the near future.

Coupling radiation from an optical fiber or laser into a waveguide device (or vice-versa) is limited by Fresnel reflection losses and the mismatch of the optical field. The former limitation can be effectively eliminated by using $\lambda/4$ thickness anti-reflection coatings. The latter may be alleviated by modifying the waveguide refractive index profile. In a semiconductor rib waveguide several parameters can be adjusted - e.g. waveguide composition, layer thicknesses, rib height, rib width. However, it is clear that the $V\pi L$ product may be compromised slightly as the guiding region thickness is varied. No systematic study on this aspect has been carried out yet, but a loss of 1dB has been measured for butt-joint coupling of an $n^-/n^+$ GaAs rib waveguide with a single mode fiber (6). Although not as good as some of the results for coupling fibers to $LiNbO_3$ devices, it is a very encouraging result, and further improvements are expected. Of course, many of these coupling problems will be considerably reduced when lasers and detectors are integrated monolithically with the waveguide devices.

## 2.3 Other Differences

Although the electro-optic coefficient and loss are generally considered the most significant differences between semiconductors and $LiNbO_3$, there are a number of other properties of relevance to waveguide devices. For the purpose of our Phase I research, we have examined them in detail.

### 2.3.1 Birefringence

$LiNbo_3$ has a high natural birefringence ($\Delta N \simeq 0.1$). Although this can be undesirable in some instances, it can also be used to good advantage in devices using TE-TM mode conversion.

In such devices, phase matching is required for coupling between the orthogonal polarisations, and this is usually achieved by some sort of periodicity in the electrode configuration. This gives a wavelength dependence which can form the basis of a filter (11). However, phase matching in $LiNbO_3$ usually results in rather narrow bandwidth operation (3.6 nm for the filter mentioned above) which will be undesirable for some applications.

III-V semiconductors on the other hand are optically isotropic and only a small birefringence is introduced when making a waveguide structure. However, it has been demonstrated that birefringence can be induced artificially by using a large number of layers of different refractive index (12). A birefringence of $\Delta N=0.055$ has been demonstrated using a GaAs/AlAs multilayer structure. Although this approach has not been pursued for device applications, it seems that this method could give great flexibility if semiconductor devices with a controllable amount of birefringence are required.

2.3.2 <u>Electrical Properties</u>

$LiNbO_3$ is an insulator, and this confers particular advantages when making composite components - i.e., integrated structures incorporating a variety of different devices. For a particular substrate orientation, different electro-optic tensor elements are needed to change the propagation constants of TE and TM modes, and yet another one to control the amount of TE-TM mode conversion. These different elements can be used by applying electric fields in different directions. An insulator is ideally suited to this approach because independent electric fields may be applied on different parts of the slice in a variety of directions.

In a semiconductor, an electric field is applied via a Schottky barrier or pn junction, and applying fields in different directions is much more difficult. In fact, to date, the only way to utilize off-diagonal tensor elements has been to use differently orientated substrates.

The normally used substrate is (001) with propagation in the <110> direction. Applying an electric field in the <001> direction changes the propagation constant of the TE mode. TE-TM mode conversion has been demonstrated by using (110) substrates with an electric field in the <110> direction (13). However, in principle it is possible to devise electrode schemes which will allow the flexibility offered by insulators (52), but the fabrication of such devices will be considerably more complex. An alternative approach would be to use high quality semi-insulating semiconductor substrate material; - with this it might be possible to use similar techniques to those used for insulators.

### 2.3.3 Speed

For conventional lumped-contact waveguide devices, the speed is limited by the RC time constant. Two factors favor semiconductors for high speed operation. First, the dielectric constant for GaAs is 5 times less than that for $LiNbO_3$ resulting in lower capacitance for similar geometries, and secondly, the capacitance of semiconductor devices is determined by the thickness of the space-charge region. This can be made very thick, if necessary, with little voltage penalty using doping profiles similar to those used in advanced III-V avalanche photodiodes (14). Thus it should be possible to reach the photon transit-time limit of 113 ps/cm without compromising other device parameters.

The ultimate speed will be obtained by using a travelling-wave (TW) electrode configuration. The performance of $LiNbO_3$ TW devices is limited by the differing electrical and optical propagation speeds. This can be overcome to a certain extent by using special electrode configurations (15) but this results in a band-pass characteristic which can be undesirable in some applications. In GaAs the dielectric constant is approximately equal to the refractive index squared so, in principle, it should be possible to achieve much higher operating speeds over a very broad bandwidth. An essential requirement for semiconductory TW devices is high quality, low loss substrate material. To date, no travelling wave devices made in semiconductors have been reported.

### 2.3.4 Acousto-optics

III-V semiconductors have not been favored for acousto-optic applications, and this might seem surprising in view of the fact that the acousto-optic figure of merit for GaAs is 15 times greater than that of $LiNbO_3$, one of the most popular acousto-optic materials. The two problems with III-V semiconductors are that i) the piezo-electric effect is very small, making generation of the acoustic waves difficult, and ii) the propagation loss of the acoustic waves in the semiconductor is very high. The generation of acoustic waves can be achieved by using a ZnO transducer (16), but on the present evidence it would seem that III-V semiconductors are unlikely to compete with $LiNbO_3$ for acousto-optic applications.

### 2.3.5 Stability, Reliability, Fabrication and Cost

A particular problem experienced with $LiNbO_3$ waveguides is the photorefractive effect - a permanent change in the refractive index profile induced by the transmitted optical flux. This has meant that optical power levels have to be kept low, and have resulted in dynamic range limitations in spectrum analyzers, and other difficulties. These problems have been alleviated to a certain extent by using longer wavelengths (1). However, a full understanding of this behavior and complete elimination of these undesirable effects awaits further detailed study. An additional problem that can occur, is ionic drift under dc operation. The remedy here is probably higher quality buffer layers (usually $SiO_2$), and again, further work is required. Another difficulty with $LiNbO_3$ is the sensitivity of some properties (notably birefringence) to temperature.

Clearly semiconductor devices have not been investigated in as much detail as $LiNbO_3$ devices, but to date no particular reliability or stability problems have been identified. One advantage here is that there is considerable experience in assessing, understanding and rectifying reliability problems with other III-V semiconductor devices, and this should be useful in speeding the progress of research-type devices towards commercial viability.

Cost may be of considerable importance in some cases - the requirement for high capacity telecommunications links in the local network could be satisfied by a fully coherent transmission system (48) rather than the conventional direct detection systems, and this would entail the use of a large number of waveguide devices. It is extremely difficult to estimate costs for waveguide devices, because, among other factors, it will depend on the complexity of the device and the numbers required. However, unlike the case of silicon devices, the cost of the starting material may be significant, particularly for the larger area devices. At the present the cost of GaAs material is between 15 and 35 per square inch, and InP between 60 and 70 per square inch. These costs are likely to reduce because of the increasing number of applications for III-V semiconductor devices (lasers, detectors, electronic ICs) and may well approach that of $LiNbO_3$ ( 8 - 25 per square inch). However, a more serious problem is the availability of sufficiently large III-V wafers. Because, in general, throughput of III-V semiconductor devices is relatively small at present, the motivation to increase slice areas from the standard 2" diameter is limited. This could present a serious limitation for the fabrication of large area semiconductor optical integrated circuits. It is hoped that larger area, high quality slices will emerge with increasing requirements for larger scale GaAs electronic integrated circuits.

At the moment, the fabrication of $LiNbO_3$ devices is relatively easy compared with semiconductor devices. It is the epitaxial growth of the semiconductor layers that is the major problem; apart from this and the chemical etching of rib waveguides, much of the rest of the fabrication is similar to that of $LiNbo_3$ (17). However, the ability to cleave semiconductors does confer advantages, and accurate polishing of the facets is not required. If MO-VPE and/or MBE can realize their potential as high yield growth processes, it may be that the fabrication of semiconductor waveguide devices will eventually not be significantly more expensive than making $LiNbO_3$ devices.

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